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A REVIEW OF THE PHYSICAL AND ENGINEERING PROPERTIES OF RAW AND RETORTED OIL SHALES FROM THE GREEN RIVER FORMATION,

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by

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The disposal of retorted oil shale is a problem of major proportion since each ton of raw oil shale entering currently used surface retort processes yields approximately 1600-1700 lb of retorted shale. Several options are available for disposal of retorted oil shales: (a) filling the deep, narrow canyons of the oil shale mine area with the spent shale, (b) backfilling the mine with spent shale as raw shale is removed, and (c) using the spent shale for productive uses. All of these options involve a determination and working knowledge of the geotechnical properties of the retorted oil shale. (Continued)

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20. ABSTRACT (Continued).

This report summarizes published geotechnical properties of raw and retorted oil shales from the Green River Formation. Basic physical properties including gradation, specific gravity and Atterberg limits and engineering properties including compaction, permeability, settlement, soundness, and strength are summarized and discussed. Where appropriate, conclusions are drawn about the suitability of retorted oil shales as a geotechnical construction material.

Appendix A discusses three retorting processes used to extract oil from oil shale.

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PREFACE

This study of the physical and engineering properties of retorted oil shales is a 2-year investigation funded by the Bureau of Mines, U. S. Department of the Interior, under Interagency Agreement H0262064. Mr. Roger A. Bloomfield, Spokane Mining Research Center, Bureau of Mines, was the Technical Project Officer.

The investigation was initiated during October 1976 by the Soils and Pavements Laboratory (S&PL) of the U. S. Army Engineer Waterways Experiment Station (WES). Dr. Frank C. Townsend, Research Group, Soil Mechanics Division (SMD), S&PL, was principal investigator during this phase of the study. The work reported herein was performed by Dr. Donald R. Snethen, Research Group, SMD, and Mr. Warren J. Farrell, Geology Branch, Engineering Geology and Rock Mechanics Division, S&PL. The report was prepared by Dr. Snethen. The investigation was accomplished under the general supervision of Mr. Clifford L. McAnear, Chief, SMD and Mr. James P. Sale, Chief, S&PL.

Director of WES during the conduct of this portion of the study and preparation and publication of this report was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
square miles	2.589988	square kilometres
acres	4046.856	square metres
pounds (mass)	0.4535924	kilograms
tons (short)	907.1847	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	6.894757	kilopascals
gallons per ton	0.0000041	cubic metres per kilogram
foot-pounds per cubic foot	47.88017	joules per cubic metre
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

A REVIEW OF THE PHYSICAL AND ENGINEERING PROPERTIES OF RAW AND RETORTED OIL SHALES FROM THE GREEN RIVER FORMATION

PART I: INTRODUCTION

1. Oil shale is a fine-grained, usually dark-colored (brown, gray, or black) sedimentary rock containing kerogen, a complex organic matter that decomposes on heating to yield oil. In the United States, the principal concentration of oil shale is in the Green River Formation in the three-state region of Colorado, Utah, and Wyoming. The Green River Formation shows the greatest promise for commercial shale oil production in the immediate future. The oil shale of the Green River Formation occurs beneath 25,000 square miles* (16 million acres) of land in the tristate area. Of the total amount, some 17,000 square miles (11 million acres) are estimated to contain oil shale suitable for commercial development (i.e., deposits at least 10 ft thick and averaging yields of 25 or more gallons of oil per ton). To be commercially feasible and operate economically an oil shale retort plant should process an estimated 25,000 to 50,000 tons of raw shale per day. Most of the currently used surface retort processes and materials produce retorted shale (spent shale, ash, etc.) at about 80 to 85 percent of total raw weight. In other words, for each ton of raw shale entering the retort plant, approximately 1600-1700 lb of retorted shale exists.

2. A major problem arises involving the efficient and safe disposal of extremely large amounts of the retorted or spent shale (over 40,000 tons per day for 50,000-ton plant). Several options are available for the disposal of retorted oil shales: (a) filling the deep, narrow canyons of the oil shale mine area with the spent shale; (b) backfilling the mine with spent shale as the raw shale is removed; and

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* A table of factors for converting U. S. customary units to metric (SI) units of measurement is presented on page 4.

(c) using the spent shale for such productive uses as aggregate in asphalt or concrete mixtures, roadway base and subbase material, drilling mud, cement production, building bricks, and mineral filler. All of these options involve a determination and working knowledge of the geotechnical properties of the retorted oil shale.

3. The purpose of this report is to summarize the published geotechnical properties of raw and retorted oil shales from the Green River Formation. The data summary provides a basis for comparison with adddiditional laboratory and field determination of geotechnical properties. The data are limited to that published on the Green River Formation of Colorado, Utah and Wyoming.

4. Possible sources of published geotechnical data were obtained through personal contacts with Federal and state agencies involved in oil shale development and through two computer based information retrieval systems: the National Technical Information Service, McLean, Virginia, and the Smithsonian Science Information Exchange, Washington, D. C.

PART II: PHYSICAL AND ENGINEERING PROPERTIES OF OIL SHALES

5. Serious interest in the production of shale oil dates back to 1920, with the interest fluctuating with the economy of the time and variations in and concern over the estimates of the domestic petroleum resources. During this period, several pilot studies and semiworks plants produced varying amounts of retorted shale; however, concern over the disposal of retorted shales and the corresponding need for quantifying the geotechnical properties did not arise until the middle 1960's. This roughly corresponds to the time frame for the major environmental protection legislation. Prior to about 1967, few, if any, geotechnical properties were determined for the retorted shale and only limited data were measured on the raw shales. Since the published data prior to this date was for raw shales only, the summary tables presented in this report were divided between raw and retorted shales with the data presented in chronological order. A survey of the information from personal contacts and computer information services resulted in 27 references[1-27] containing data pertinent to geotechnical properties of raw and retorted shales. Table 1 summarizes general information pertinent to the entries in the tables of properties for specific references. Tables 2 and 3 summarize the physical and engineering properties of raw oil shales. Table 4 summarizes physical and engineering properties of retorted oil shales. In subsequent paragraphs, data for both raw and retorted shales will be discussed in detail with emphasis on retorted shale properties.

Physical Properties

6. The physical properties of interest to geotechnical engineers are specific gravity, gradation, and Atterberg limits. Of equal importance but not considered to be a physical property is the classification of the material using either the Unified Soil Classification System (USCS) or the American Association of State Highway and Transportation Officials (AASHTO) system.

Specific gravity

7. The specific gravity may be expressed in three forms: (a) the specific gravity of solids, which is applied to soils finer than those passing a No. 4 sieve; (b) the apparent specific gravity; and (c) the bulk or mass specific gravity. Both the apparent and mass specific gravities are applied to soils coarser than the No. 4 sieve with the apparent specific gravity routinely used when dealing with coarser materials. The average value of the apparent specific gravity of raw oil shale (Tables 2 and 3) varied from 2.02 to 2.36. The apparent specific gravity was generally greater for the low-kerogen content shales and decreased with increasing kerogen content. No significant difference was noted between the samples taken parallel and perpendicular to the shale bedding planes. Mass specific gravity, available from only one reference,[26] and ranged between 1.99 and 2.20. For the retorted shales, the apparent specific gravity ranged between 2.11 and 2.59 with the majority of the values between 2.52 and 2.59. Mass specific gravity available from two references ranged between 1.80 and 1.85. These specific gravity values are quite low in comparison with sandstone, limestone, basalt and granite rockfill materials with values reported ranging from 2.29 to 2.84 for mass specific gravity and 2.65 to 2.87 for apparent specific gravity.

Gradation

8. The gradation of raw shale provides very little useful information since the gradation is dependent on mining operations and the type of crusher and amount of crushing the material undergoes prior to retorting. Of greater significance is the gradation of retorted shales, since it is helpful in classifying the material and thus qualitatively indicating the suitability of the material for engineering purposes. The influence of the retorting process on gradation is evident in Figure 1, which shows the gradation of a raw and retorted shale. As would be expected, the retorting process breaks down the raw shale. For example, the < No. 40 fractions for the raw and retorted shales are 43 and 62 percent, respectively. The < No. 200 fractions for the raw and retorted shales are 11 and 37 percent, respectively. Appendix A gives a

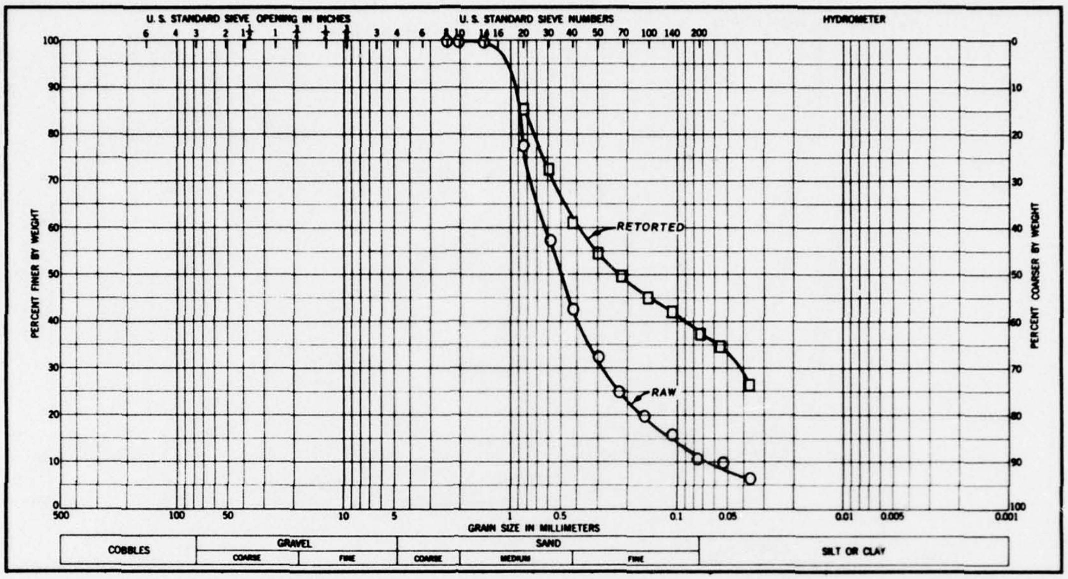

Figure 1. Comparison of raw and retorted oil shale gradations (from Reference 10)

detailed description of several different retorting processes. A fundamental difference in the raw shale gradations of the gas-combustion process (Paraho process) and the Tosco process exists. Specifically, the Paraho process uses the material between the 3- and 3/8-in. particle sizes while the Tosco process operates on <3/8-in. particle sizes. In the Paraho Study[26] the raw shale retort feed, raw shale reject, and three combinations of the two raw shale gradations were tested to obtain geotechnical properties of the raw materials. Figure 2 shows the two basic gradations (A and C) and the combinations (gradations B, D, and E). The raw shale feed, as screened, was 100 percent gravel-size particles. The raw shale reject contained 45 percent gravel-size, 48 percent sand-size, and 7 percent silt- and clay-size particles. The variability of the gradation for various retorted shales is evident in Table 4. The gravel-size particles ranged from zero to 79 percent and the silt and clay size from zero to 63 percent. Samples in which the percent <0.005 mm (clay) was determined ranged from zero to 12 percent. The uniformity coefficients for nearly all of the retorted samples were high with values beginning at 4.7 and going up to as high as 1822. The higher

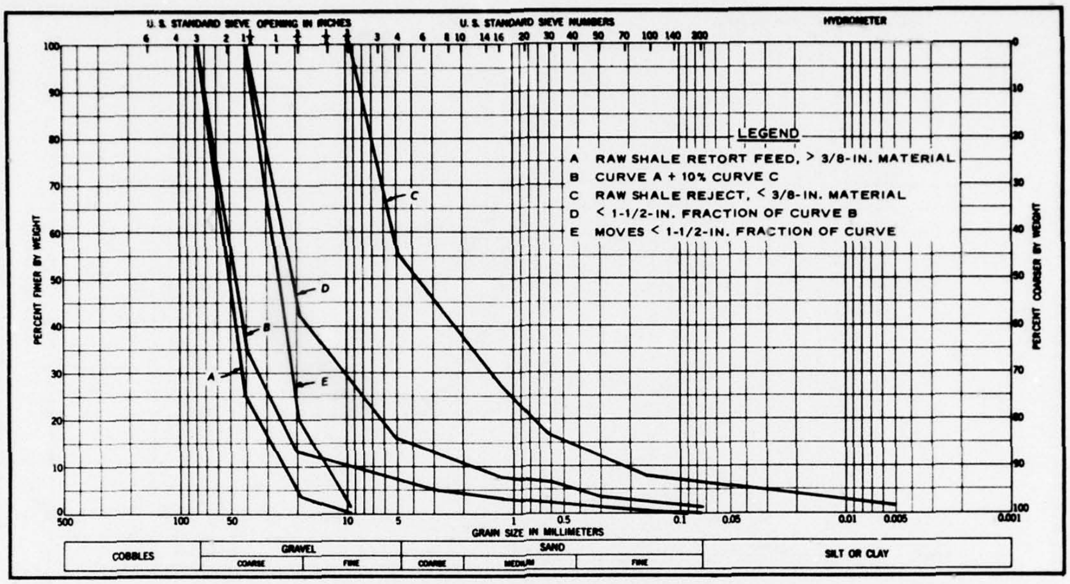

Figure 2. Gradations of raw shale samples used on Phase VII of Paraho Oil Shale Project (from Reference 26)

uniformity coefficients indicate a well-graded (or nonuniform for the geologist) sample, which is generally more desirable when compaction and strength properties are important.

Atterberg limits

9. Atterberg limits represent the end points and range of water contents over which the consistency of the material varies. No Atterberg limit data are available on the raw shales, and only a very limited amount is available for the retorted shales. Generally, the retorted materials are nonplastic. The two reported values of Atterberg limits showed liquid limits of 30 and 33 and plasticity indexes of 6 and 3, respectively.

Soil classification

10. Under the USCS, the retorted shales would be classified as GM, SM, or ML depending on the amount of gravel present in a specific sample and the plasticity of the fines. Under the AASHTO system, the retorted shales would be classified as A-1 or A-3 materials. In general, the classifications indicate good compaction characteristics, slight to medium compressibility, good to excellent strength values, and overall, a

good foundation material. Classification of the raw shale is of little consequence since it is considered to be rock in its in situ state, and classification based on gradation is meaningless because of the man-made variability of the gradation (i.e., different crushers and amount of crushing).

Engineering Properties

11. The major engineering properties pertinent to geotechnical engineers are compaction, permeability, consolidation or settlement, durability, and strength. As previously noted, engineering properties were not determined for retorted materials prior to the middle 1960's. In addition, the engineering tests that were conducted were run primarily on undisturbed cores with the data being used to determine mine roof and pillar strength and stability. Only one reference reported test data on raw crushed shale.[26] Beginning in the middle 1960's, disposal of retorted oil shale became a major concern. Disposal and/or alternative uses of spent shale necessitated the characterization of the material from an engineering viewpoint. The following discussions of engineering properties will be presented in the same chronological order: undisturbed raw shale, crushed raw shale, and retorted shale.

Compaction

12. Only one reference reported laboratory compaction characteristics for crushed raw shale.[26] Two of the gradations shown in Figure 2 (curves D and E) were tested at two different compaction energies (one half the American Society for Testing and Materials (ASTM) Standard[28] D 698 or 6,200 ft-lb/ft^3, and ASTM D 698, or 12,375 ft-lb/ft^3. The resulting optimum moisture contents and maximum dry densities were 6.0 percent and 88.3 pcf for the low compaction and 8.3 percent and 90.3 pcf for the standard compaction for gradation curve D. Corresponding values for curve E were 1.0 percent and 77.5 pcf for the low compaction and 1.0 percent and 80.1 pcf for the standard compaction. As would be expected for compaction of granular or gravelly materials, the variation of dry density through the range of moisture content tested was very small; dry

density varied from 89 to 91 pcf for a 10 percent change (0 to 10 percent) in moisture content.

13. Considerable effort has been expended in developing the laboratory compaction characteristics of retorted oil shales since the importance of compaction on the evaluation of disposal alternatives has been determined. In addition, compaction of the retorted shales influences the other engineering properties. The major variable in establishing the compaction characteristics was compaction energy, with five levels of compaction energy reported. The five levels and their corresponding ranges of optimum moisture content and maximum dry density are presented in the following tabulation:

Compaction Energy $ft\text{-}lb/ft^3$	ASTM Standard	Optimum Moisture Content, percent	Maximum Dry Density, pcf
6,200	D 698 (50 percent)	18.5-27.2	77.0-99.2
12,375	D 698	15.5-31.0	78.6-103.2
19,700	D 1557 (35 percent)	22.0	93.2-94.0
33,750	D 1557 (60 percent)	17.4	106.7
56,250	D 1557	14.2-22.0	88.8-109.2

Other trends not obvious in this tabulation but apparent in Table 4 include (a) the obvious trend of lower optimum moisture content and higher maximum dry density with increasing compaction energy and (b) the accepted trend of higher optimum moisture contents and lower maximum dry densities with decreasing maximum particle size (i.e., more sands, silts, and clays). The characteristic of small dry density changes over the molding moisture content range exhibited by the crushed raw shale is also predominant for the retorted materials. The range of maximum dry densities of the compacted retorted shales under standard compaction energy is somewhat less than would normally be anticipated for a GW soil, which would normally range from 120 to 135 pcf.

14. Laboratory compaction data provide extensive insight into the

behaviorial characteristics of compacted soils. However, because of the limited knowledge of the engineering properties of retorted oil shales, the effectiveness of field compaction equipment in achieving the desired density conditions is a question of considerable concern. To determine this effectiveness, the Paraho Oil Shale Project undertook the construction of an extensive compacted test fill.[25] The major variables in the test fill study were moisture added, loose lift thickness, type of compaction equipment, and number of passes. Table 5 summarizes the test fill study. The results tabulated in Table 5 are shown graphically in Figure 3. For the 8-in. loose lift thickness with moisture added at the test fill, the highest percent compaction was achieved with the vibrating drum compactor (6 passes) followed by the vibrating pad (5 passes), tractor (6 passes), rubber tire (6 passes), and sheepsfoot (6 passes) compactors. Combinations of the compaction equipment provided significant percent compactions, i.e., vibrating pad plus vibrating drum (4 passes each) and sheepsfoot plus rubber tire (4 and 6 passes, respectively). For the 12-in. loose lift thickness, the vibrating compactors were significantly better than the conventional compactors. The same percent compaction was achieved as was obtained using the vibrating compactors on the 8-in. lift; however, twice as many passes had to be made on the 12-in. thickness. For the test fill with no moisture added and an 8-in. loose lift thickness, the highest percent compaction was achieved with the vibrating drum compactor (6 passes) followed by the tractor (6 passes) and the remaining three compactors resulting in the same percent compaction (98 percent). Other than the one high point (104 percent) and one low point (92 percent) at 6 passes, the remainder of the compaction data (without moisture) fall within a fairly narrow band of percent compaction between 95 and 102 percent. This indicates that without adding water, the density of retorted shale cannot be significantly increased by varying the type of compactor or increasing the number of passes for a particular compactor. Based on these field data, the most economical compaction would be obtained using a vibrating drum compactor with either 8- or 12-in. lifts with increasing lift thickness requiring additional passes. Slightly higher densities can be obtained

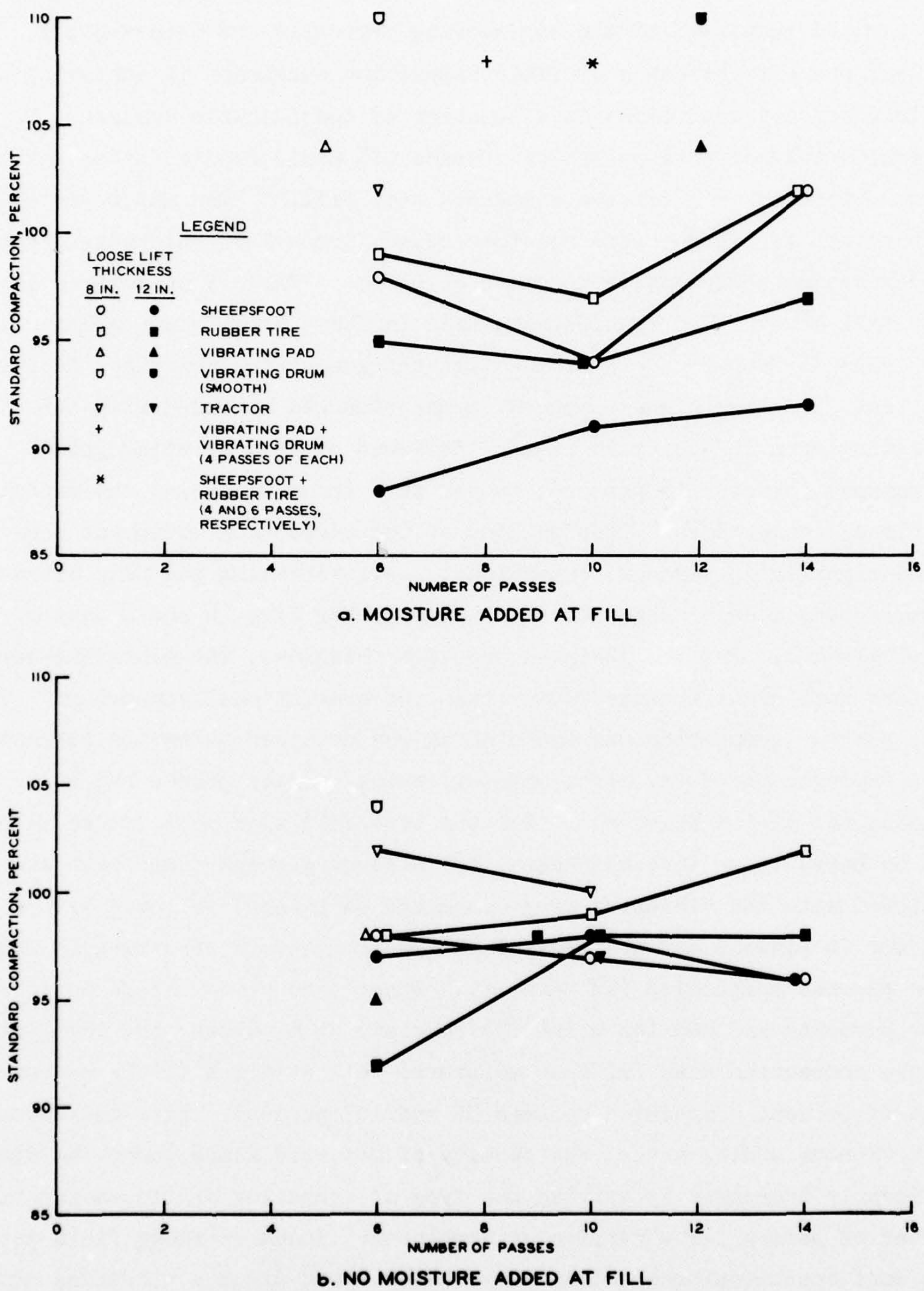

Figure 3. Summary of results of compacted test for study, Paraho Oil Shale Project (from Reference 25)

by adding water; however, the cost of hauling and distributing water may be prohibitive.

15. Table 5 shows the breakdown of the retorted shale by the various compactors. Based on an average of all tests conducted, 10 percent of the gravel-sized particles were broken down into the sand-, silt-, and clay-size fractions. Particle breakdown was less for the wet fill than for the dry fill construction.

16. Based on results of the test fill study, the filtration test pond lining (Pond No. 1) was compacted using a vibrating drum compactor. An average percent compaction of 98 percent was achieved. A discussion of the filtration test ponds will be presented in subsequent sections.

Permeability

17. The permeability of raw oil shale is an important property when considering in situ retorting of the shale. Permeability during in situ retorting is dependent on the temperature and pressure applied during the process.[13,20] Permeability values for compacted raw shales, reported in one reference,[26] ranged from 10,500 to 14,500 ft per year (uniaxial loading = 4 psi) for 3/8- and 1-1/2-in. maximum particle sizes, respectively. For retorted shales, the permeability is important when considering the stability of embankments constructed of the material and the pollution potential of rainwater leaching chemicals out of the disposed shale. Under various loadings, the permeability varied as indicated in the following tabulation. No definite trends were obvious from these data, which show that considerable variation exists in permeability values. However, accepted trends such as decreasing permeability with increasing density and increased percent of fines were verified. The amount of carbonate decomposition during retorting appeared to have a significant influence on permeability: the higher the decomposition, the greater the permeability. Since engineers are more familiar with permeability presented in units of centimetres per second, the values in the following tabulation and Tables 3 and 4 can be converted by multiplying feet per year by 0.97×10^{-6} to obtain centimetres per second.

Load (uniaxial) psi	Permeability ft per year	Dry Density pcf
50	0.3-71	98.9-93.9
100	0.25-52	98.9-93.9
200	0.08-30	98.7-93.9
70	1.5-2088	96.7-77.0
145	1.19-1016	96.7-77.0
300	0.3-480	96.7-77.0
1000	4.72-14.5	96.6-80.2

18. Field studies of the permeability of retorted oil shales were conducted during the Paraho Oil Shale Project[27] (Phase VII). In two filtration ponds, one with a compacted lining and the other with an uncompacted lining, the seepage and evaporation were monitored. The uncompacted lining was found to have an average permeability of 2039 ft per year while the compacted lining was found to have an average permeability of only 4.24 ft per year. For comparison, laboratory permeabilities on 6-in.-diam cores from the compacted lining ranged from 0.16 to 1.18 ft per year.

Settlement (consolidation)

19. Settlement (consolidation) properties are of minor consequence for raw oil shales, but are very important in assessing the stability of an embankment constructed of retorted shales since excessive settlement could cause such an embankment to become unstable. In addition, consolidation of retorted shale influences its permeability and strength characteristics as well as the total volume required in a disposal site.

20. One reference reported settlement properties on compacted raw shales[26] with several references reporting on retorted shale.[18,22-24] The percent settlement for the various applied loads (ASTM D 698 energy) is summarized in the following tabulation:

Material	Applied Load psi	Settlement percent	Dry Density pcf
Paraho	50	0.7-2.8	95.5-88.0
	100	0.8-3.4	95.5-98.3
	200	0.8-4.8	95.5-98.3

(Continued)

Material	Applied Load psi	Settlement percent	Dry Density pcf
Paraho	70	0.4-3.4	88.8-102.5
	145	0.7-4.8	85.0-97.4
	300	0.8-5.6	85.0-97.4
	1000	5.3-10.7	80.2-96.6
Tosco	100	0-15.5	86.6-56.5
	200	0.5-18.0	86.6-56.5
	1000	1.0-23.0	86.6-56.5

The common trend of decreasing settlement with increasing density was not apparent for the ranges of settlements obtained for the Paraho material; however, the trend was obvious for the Tosco material. This is probably a result of the limited range of densities tested for Paraho samples compared with that of the Tosco samples. Quantitatively, the minimum percent settlements are well within tolerable limits for nearly any application. In general, the maximum percent settlements up to about 5 percent are tolerable if an adequate design is prepared to accommodate the settlements. In other words, for both materials, settlement can be effectively minimized by adequate compaction. No detectable difference was noted between the materials retorted by the direct or indirect heating modes. In the Paraho Oil Shale Study, the low carbonate decomposition retorted shales settled roughly 1-1/2 to 2 times as much as the high carbonate decomposition shales.[23] Adding raw shale reject material (<3/8 in.) to different carbonate decomposition samples reduced overall magnitude of settlement; however, the same trend of increasing settlement with decreasing carbonate decomposition was evident.

Soundness

21. The soundness of an aggregate material is a measure of its ability to resist degradation from an applied force. Generally, soundness is quantified using the Los Angeles Abrasion (LAA) test. For the raw shale feed, the LAA value was 14 percent (material loss), which indicates a high degree of soundness. Many State Highway Agencies require maximum loss values for concrete and base course aggregate of 40 percent. The LAA values for retorted shales varied from 21.5 to 70 percent loss. The sample with the 21.5 percent loss was taken from the

U. S. Bureau of Mines (USBM) Demonstration Plant Stockpile and had been exposed to the climate for several years. The suggested reason for the low LAA value was that the softer particles deposited in the stockpile had probably broken down, leaving only the hard, sound rocks that were eventually tested. The more recent samples probably still include these softer materials within the gradation normally tested in the LAA device; hence, the high values of degradation.

Strength

22. The strength characteristics are most important in determining the stability or load-carrying capacity of the raw or retorted oil shale. Strength has been quantified using several parameters and tests: modulus values, unconfined compressive strength q_u, and triaxial shear strength ϕ, C. Prior to the mid-1960's, no strength tests were conducted on retorted shale. The only strength determinations made were on undisturbed cores of raw shale to determine the size and stability of underground mine openings.

23. Intact raw shale. The average q_u of undisturbed raw shale cores varied between 9,660 and 25,700 psi. The major variables investigated in the strength determinations were kerogen content and core sample orientation (parallel or perpendicular to bedding). Compressive strength was greater for the low-kerogen-content shales, with the ratio of low- to high-kerogen-content compressive strengths in excess of two. Differentiation on the basis of core sample orientation was not as evident; however, in most cases the horizontally oriented (parallel to bedding) cores yielded slightly higher strengths. During the Paraho Oil Shale Project, q_u values were determined on core samples taken from large mine-run blocks. Values of q_u varied from 7,540 to 10,027 psi.

24. Leps[30] classified rockfill on the basis of unconfined compressive strength of rock cores in the following manner:

q_u, psi	Strength Classification
500-2,500	Weak rock particles
2,500-10,000	Average rock particles
10,000-30,000	Strong rock particles

Based on this classification, most of the raw shale would be considered strong rock particles. The raw Paraho material exhibits the strength of average rock particles.

25. Modulus values were determined for use in the roof and pillar designs; however, the modulus of elasticity was the one most used and most easily identifiable. The average modulus of elasticity for undisturbed core samples varied from 0.83×10^6 to 6.025×10^6 psi. As expected, trends identical to those set for the compressive strength were obtained for the modulus of elasticity, namely, increasing modulus values with lower kerogen contents and horizontally oriented samples. The other modulus values, rupture and rigidity, along with Poisson's ratio ν for raw shale are summarized in Tables 2 and 3. Modulus of elasticity values ranged from 0.56×10^6 to 0.82×10^6 psi, and ν varied from 0.28 to 0.36 (values determined using shear wave tests).

26. <u>Compacted raw shale.</u> For crushed raw shale, in particular the <1-1/2-in. shale feed reject compacted at ASTM D 698 and one half ASTM D 698 compactive efforts, the friction angle ϕ values were 39 and 35 deg, respectively. Cohesion c values for the ASTM D 698 and one half ASTM D 698 efforts were 19.4 psi (13.9 psi for saturated specimens) and 22.9 psi (15.3 psi for saturated specimens), respectively.

27. <u>Compacted retorted shale.</u> Strength characteristics are most significant from an engineering viewpoint when considering the disposal of retorted shales. The parameters used to quantify the strength characteristics in the reported data were ϕ , c , and q_u .

28. Retorted materials compacted at 10 percent ASTM D 698 compaction energy were tested in unconsolidated, undrained (Q) triaxial and unconfined compression tests by the University of Denver.[15] The results of the unconfined compressive testing program are shown in Figure 4 and the triaxial testing program in Figure 5. The q_u increased with storage or curing time, increasing storage or preconsolidation pressure for constant curing time, and increasing molding water content. This latter trend is contrary to accepted trends for this general type of material (i.e., GW, ML); however, it may be explained on the basis of one of two arguments. The first argument involves the more extensive development

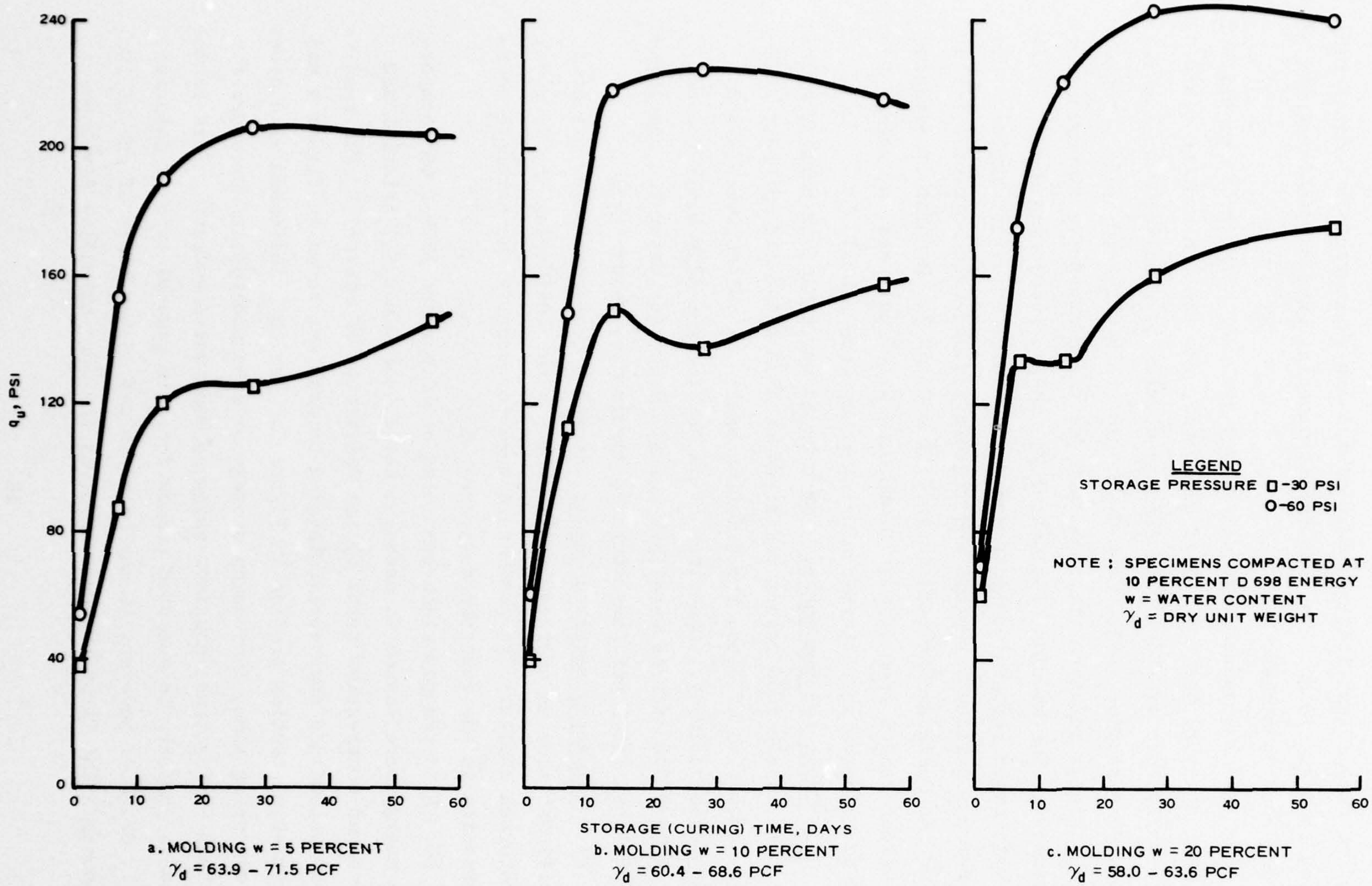

Figure 4. Influence of water content, storage time and storage pressure on q_u (from Reference 15)

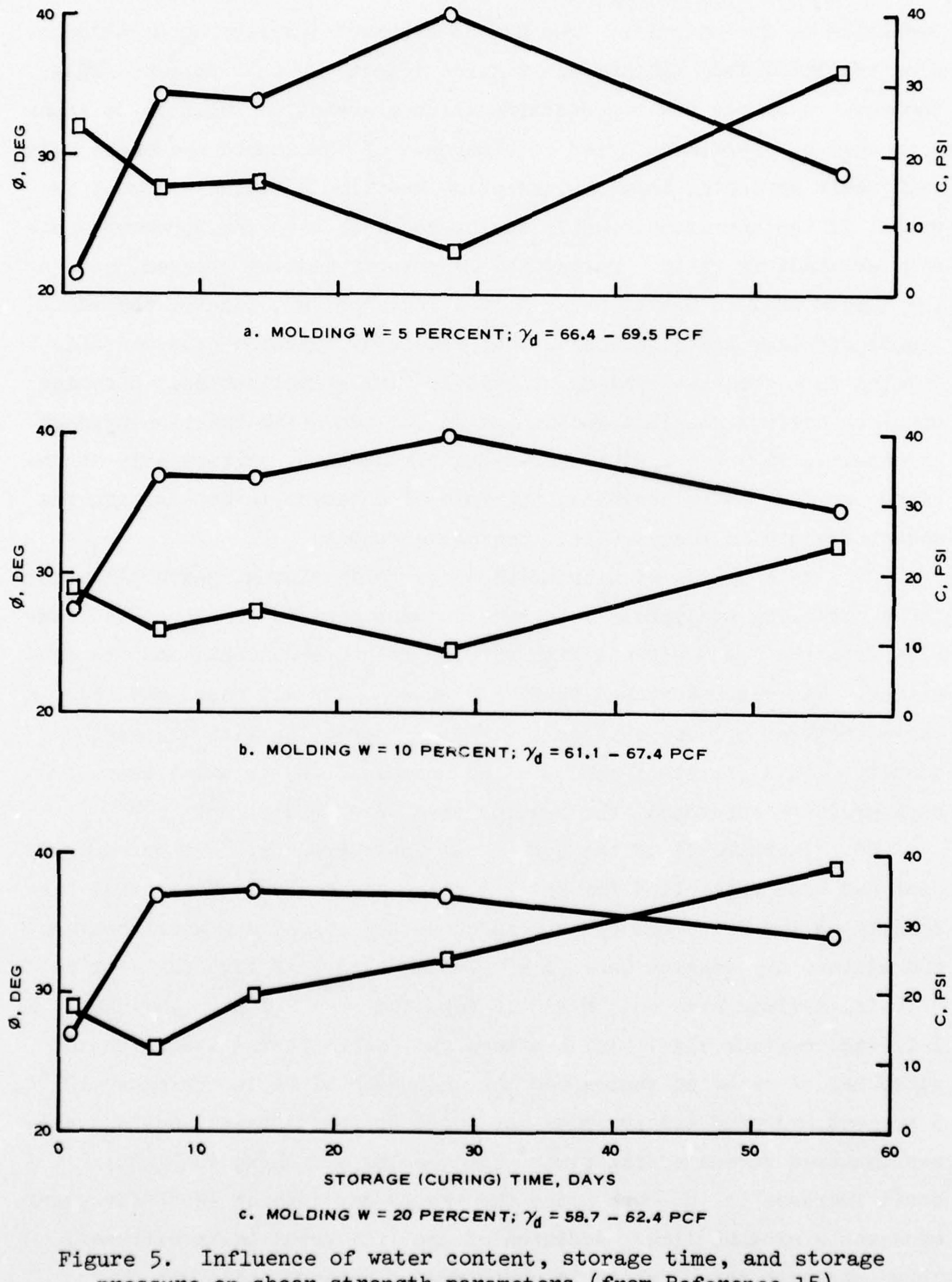

Figure 5. Influence of water content, storage time, and storage pressure on shear strength parameters (from Reference 15)

of cementitious reaction products as a result of the extra water made available to the material. The second argument involves apparent cohesion resulting from the surface tension effects of the increased water content. A simple way to determine which argument is valid is to inundate the q_u specimens prior to testing. If the soaked specimens maintain their strength, then the cementing reaction products argument is valid; if the specimens crumble during soaking, then the apparent cohesion argument is valid. During the laboratory testing program, none of the specimens were soaked prior to testing; however, some of the additional chemical tests indicated that cementing reaction products did develop in a somewhat similar process to lime stabilization. A second and less obvious possible indication of the cementing reaction product is shown in Figure 5. With increasing curing time, particularly at the higher molding water contents, the role of cohesion in determining the shear strength increases (i.e., the curves cross).

29. In a series of Q triaxial tests to develop strength parameters for a stability analysis,[18] ϕ and c were measured on compacted samples from the Tosco process with varying moisture contents and dry densities. The results showed that $\phi = 35$ deg for all tests and that c varied between 6.3 and 19.4 psi, with c increasing with increasing density. In a series of consolidated undrained (R) triaxial tests, back-pressure saturated, the results were $\phi = 20$ deg and $c = 0$.

30. In Phase II of the Paraho Oil Shale Project,[22] retorted shale that had been stockpiled for several years was tested. R triaxial test results on two different gradations compacted at optimum water content and maximum dry density were $\phi = 32.4$ deg and $c = 17.4$ psi for the 3/16-in. maximum size and $\phi = 34.2$ deg and $c = 2.2$ psi for the 1-1/2-in. maximum size. In an attempt to determine the stabilization potential of retorted shales and the influence of rapid curing at 125°F, 5 percent hydrated calcium lime was added to the material and q_u values measured versus curing time. The results are shown in Figure 6. A small increase in q_u was noted for the 28-day cure at 125°F for specimens containing no lime. Addition of the lime resulted in extremely large strength gains, which is most unusual because soils with

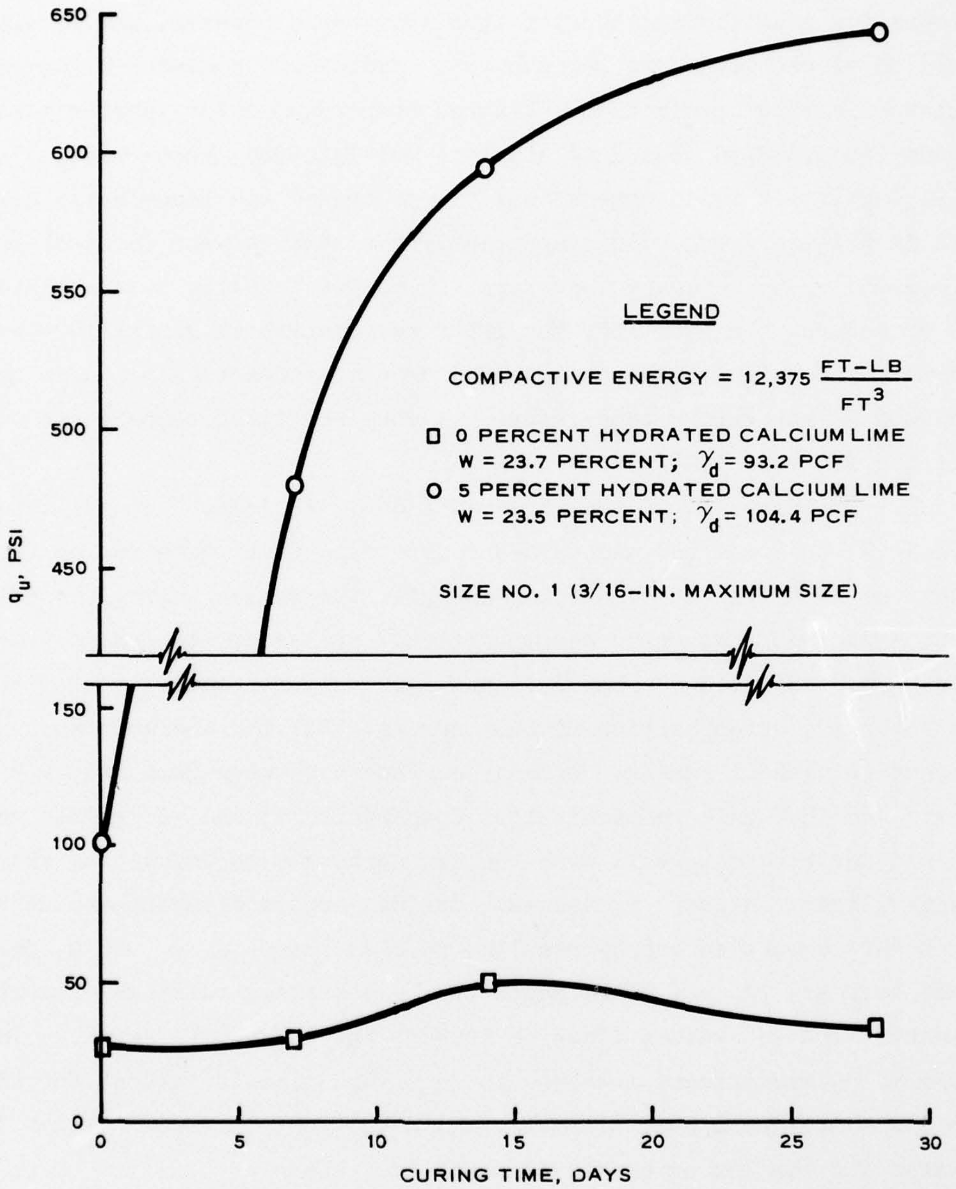

Figure 6. Influence of curing time and lime treatment on q_u (from Reference 22)

plasticity indexes less than 10 do not respond to lime treatment. The strength gains obtained would far exceed any of the generally accepted criteria for quantifying stabilization potential; however, the results should be viewed with some reservation. Rapid-cure procedures generally consist of curing specimens at elevated temperatures for shorter time periods (i.e., 30-90 hours) to simulate multiple-day curing (i.e., 7, 14, 21 days). It would appear that the procedure was incorrectly applied in this reference since apparently the samples were cured at 125°F for periods up to 28 days; therefore, it is not actually a true rapid-cure procedure. In addition, the 125°F temperature is generally considered to be too high since the type and amount of reaction products are dependent on the curing temperature. A more realistic temperature would be in the range of 100-105°F.

31. In Phase III of the Paraho Oil Shale Project,[23] consolidated, drained (S) triaxial and unconfined compression tests were run on three gradations at different compaction energies for shales having two different amounts of carbonate decomposition. Values of ϕ and c ranged between 35.0 and 37.6 deg and 12.5 and 13.9 psi, respectively, for the high carbonate decomposition without curing. For the low carbonate decomposition without curing, ϕ and c ranged between 34.2 and 42.9 deg and 9.7 and 13.2 psi, respectively. Comparable ϕ and c values were obtained for both materials with the low carbonate decomposition shale showing slightly higher ϕ values. Curing comparable specimens at ASTM D 698 compaction energy resulted in a decrease in ϕ and a considerable increase in c , which supports the cementing reaction product argument. The q_u values likewise support this argument, as shown in Figure 7. A significant increase in q_u with time is evident for the high carbonate decomposition shale, while the q_u increase is much less dramatic for the low carbonate decomposition shale.

32. In Phase IV[24] of the Paraho Oil Shale Project, S and K_o triaxial and unconfined compression tests, where K_o is the ratio of lateral stress developed to vertical stress applied, were run on retorted shales produced by direct and indirect heating modes of the retort plant. The variables studied during the testing program were

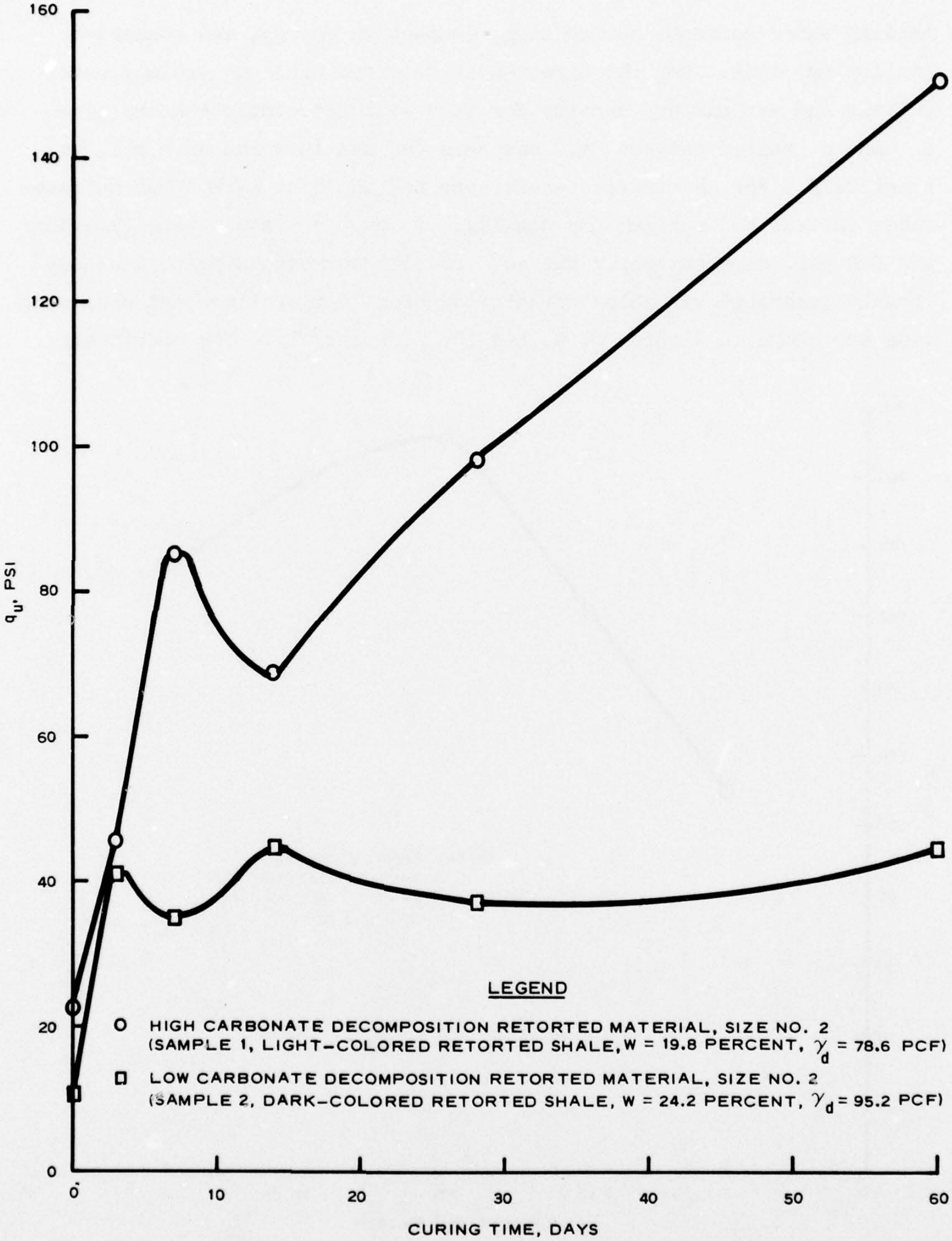

Figure 7. Influence of curing time on q_u for high and low carbonate decomposition materials (from Reference 23)

molding water content, curing time, compaction energy, and seasoning (mellowing) time. For the direct-heat retorted shale at optimum water content and maximum dry density for each of three compaction energies, ϕ and c ranged between 34.2 and 34.6 deg and 19.4 and 36.1 psi, respectively. For the indirect-heat retorted shale at ASTM D 698 optimum water content and maximum dry density, ϕ and c values were 29.2 deg and 3.0 psi, respectively. The q_u results corresponding to the previously described variables of water content, curing time, and seasoning time are shown in Figures 8, 9, and 10, respectively. The previously

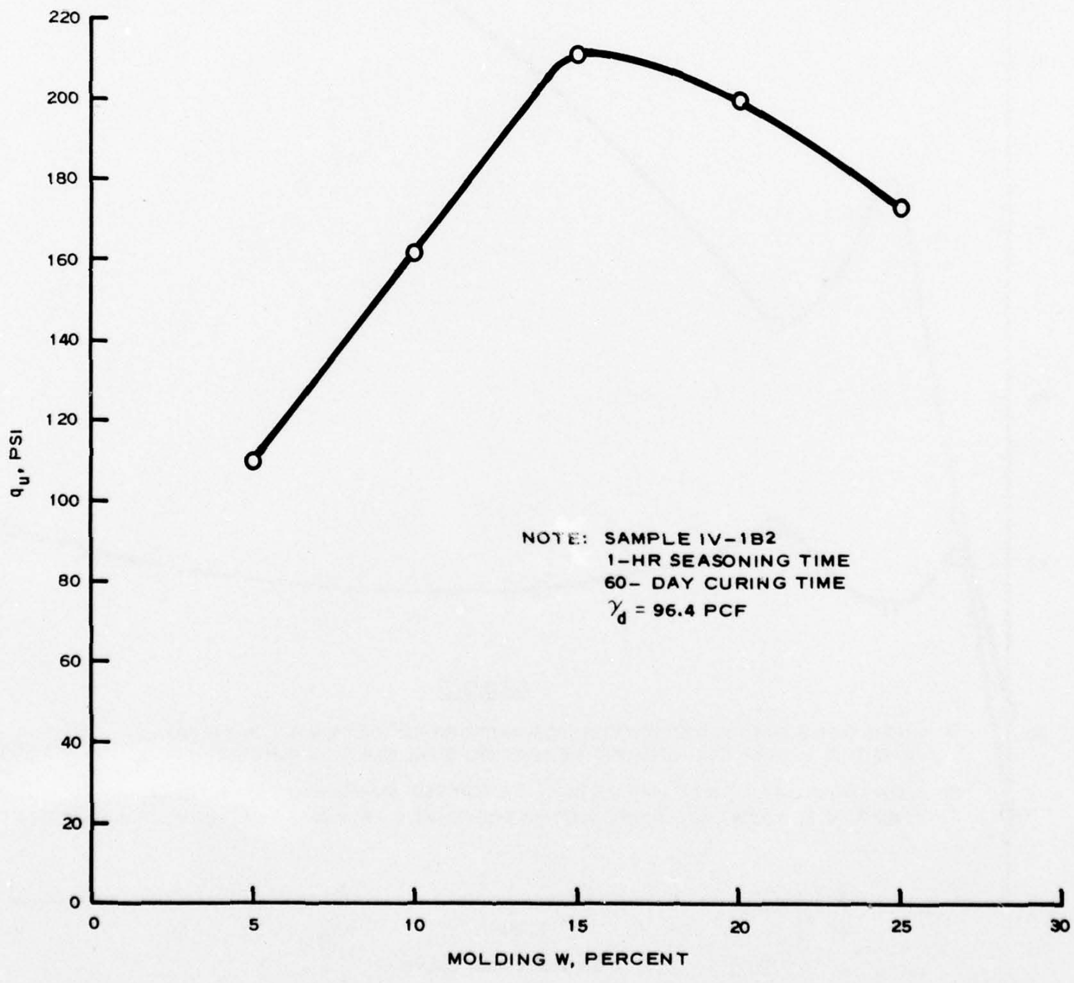

Figure 8. Effect of molding water content on q_u (from Reference 24)

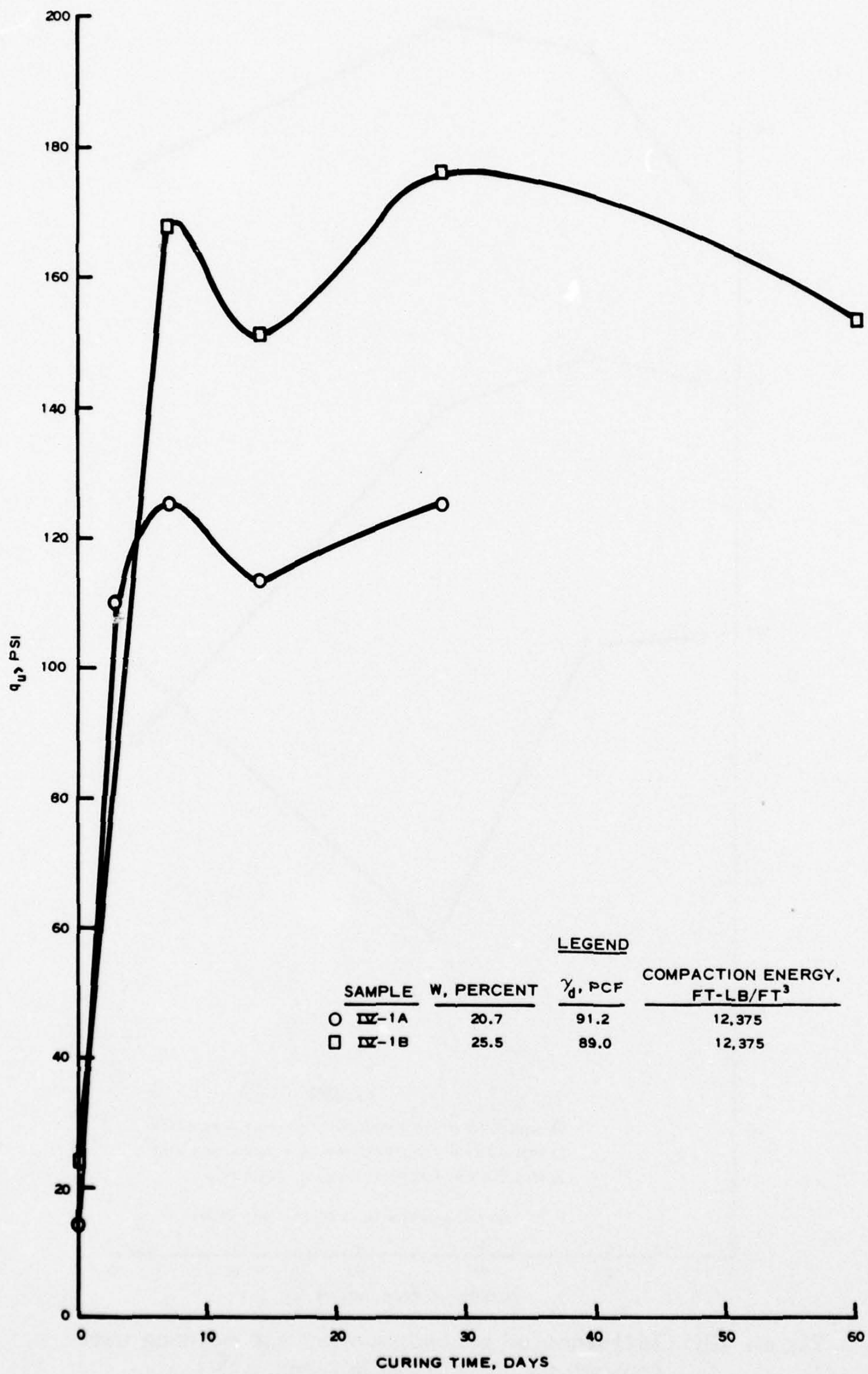

Figure 9. Influence of curing time on q_u
(from Reference 24)

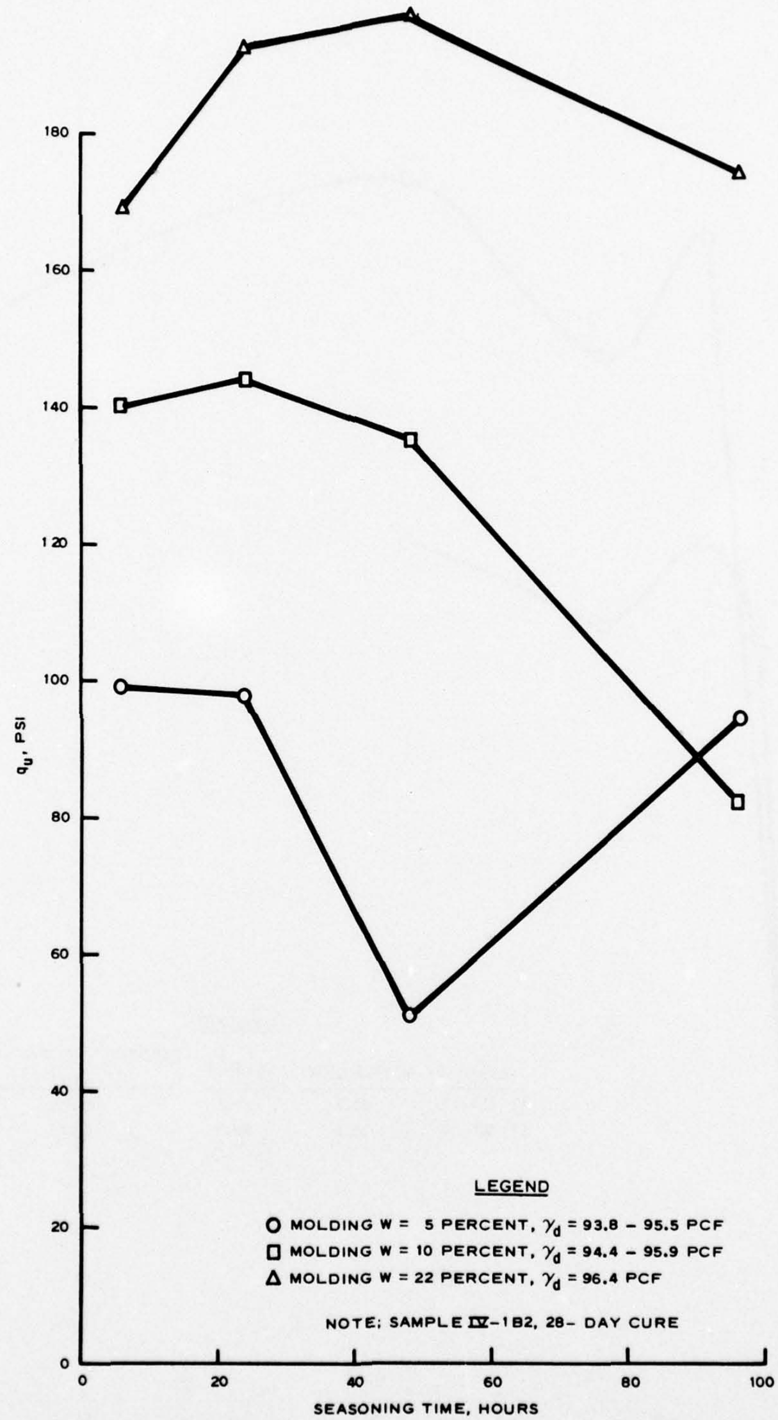

Figure 10. Influence of seasoning time and molding water content on q_u (from Reference 24)

described trend for retorted shales of increasing q_u with increasing water content was again evident up to a molding water content of 15 percent. Above 15 percent, the strength began to decrease, probably due to the fact that excess water was available in the specimen. The cementing reaction product effect is again evident in Figure 9 as the strength increased with time.

Influence of mellowing time

33. In lime stabilization, the development of pozzolanic (cementing) reaction products occurs at the contact points between particles when the lime reacts with surfaces of the individual particles and forms the cementing agent. This reaction and the corresponding cementing action occurs relatively fast, requiring that the particles be in close proximity (i.e., compacted) within a reasonably short time (i.e., 24 to 48 hours) after the lime is introduced into the soil. The influence of seasoning or mellowing time for retorted oil shales is comparable to that of lime-stabilized soils (Figure 10). At the lower molding water contents, the strength drops off rapidly after approximately 24 hours if the specimens are not compacted by that time. With increasing molding water content, q_u increases and the seasoning time before strength begins to decrease is extended. This is the result of the additional water being available to enhance the amount of the reaction and extend the reaction time. In other words, at the lower water contents the amount of development of reaction products and length of time for development is less because sufficient water is not available.

K_o tests

34. During the K_o triaxial testing program,[24] duplicate specimens were prepared and tested in unconfined compression. The major variables investigated in the testing program were gradation, compaction energy, and addition of additives (1 and 3 percent lime and cement). The purpose of the testing program was to compare modulus of deformation E_d values with such properties as q_u , K_o , and ν . The results of the K_o and q_u tests are summarized in Table 4 and shown graphically versus the previously mentioned properties in Figures 11, 12, and 13. Although the q_u values for the 60-day cure specimens did

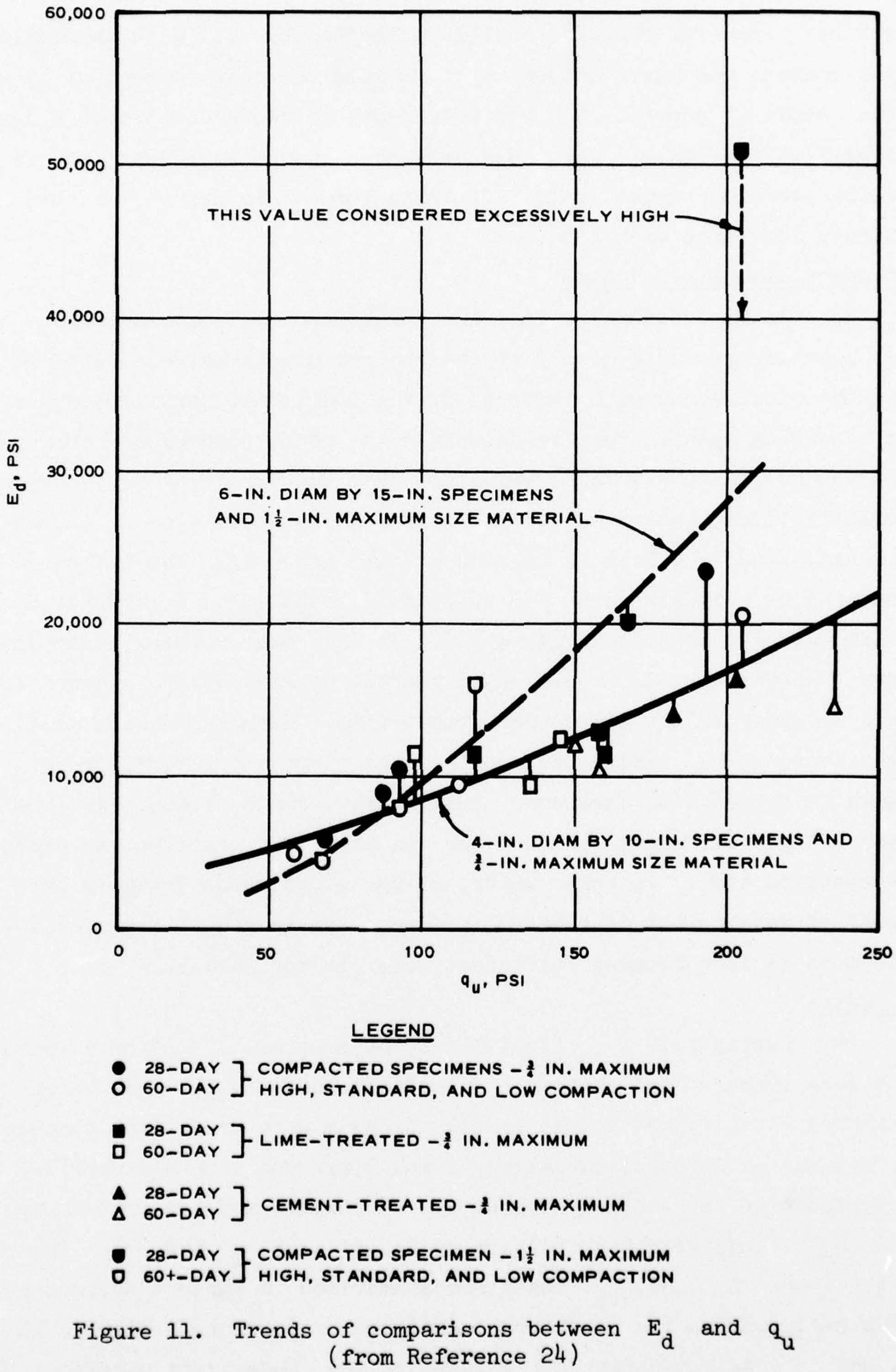

Figure 11. Trends of comparisons between E_d and q_u (from Reference 24)

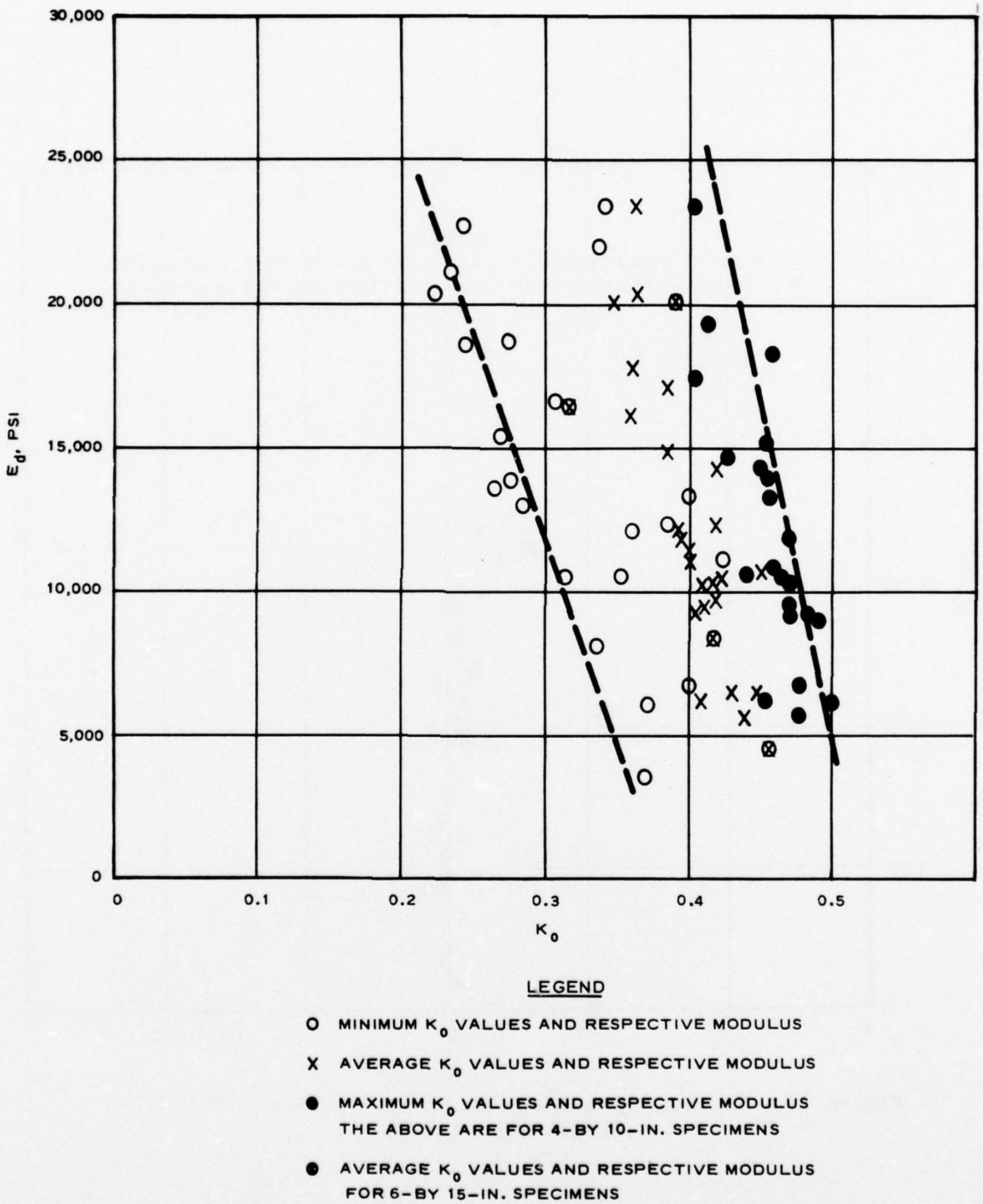

Figure 12. Summary of K_o results (from Reference 24)

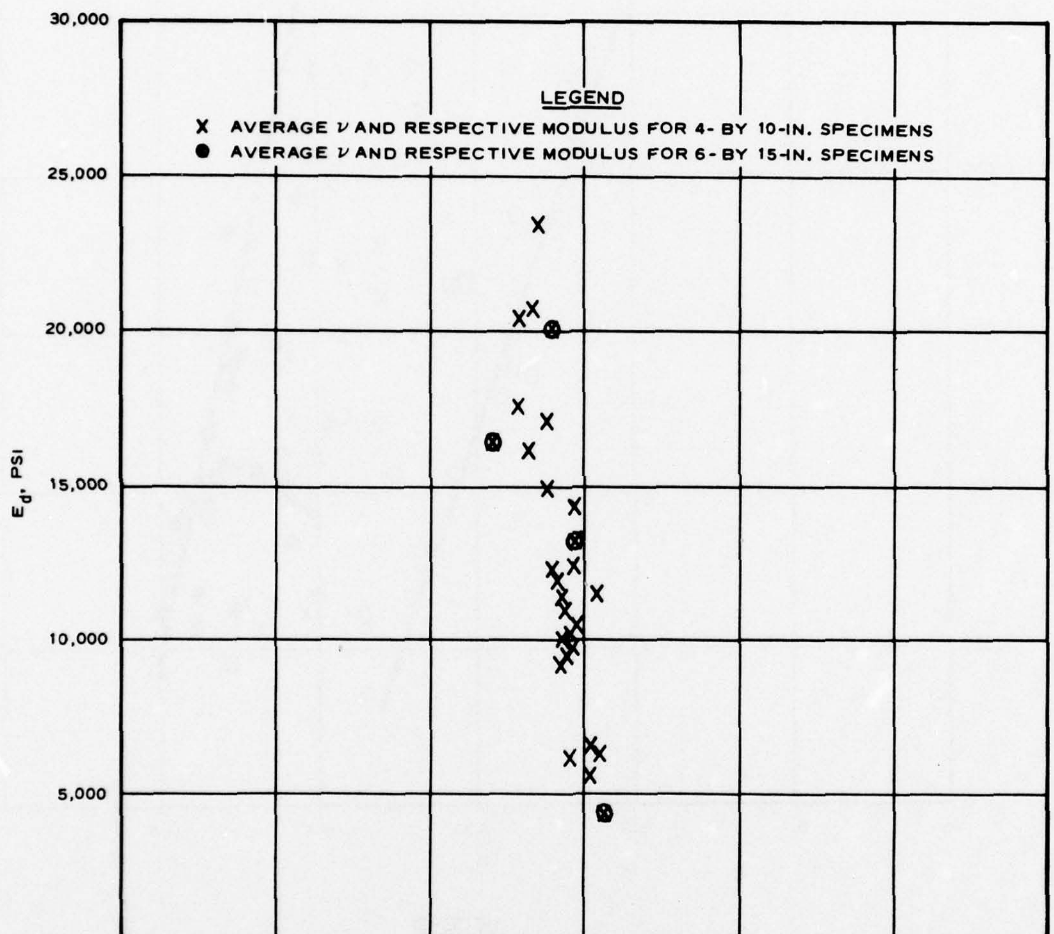

Figure 13. Summary of average values of Poisson's ratio ν (from Reference 24)

show some slight increase over the 28-day cure specimens, on the whole there was very little discernible difference. This would indicate that the cementing action that develops with time is essentially developed prior to the 28-day cure limit. This finding is consistent with all of the previous testing results. As expected, increased compaction energy resulted in higher q_u values. Addition of 1 percent hydrated lime resulted in a distinct improvement in q_u, i.e., 159.2 psi and 136.2 psi for 28- and 60-day cures, respectively, as compared with 88.2 psi and 103.1 psi for the 30- and 60-day cures, respectively, without lime. Addition of 3 percent lime actually resulted in a decrease in q_u values, i.e., 117.9 psi and 122.3 psi for 28- and 60-day cures, respectively. The probable explanation for this decrease is the hydration of the excess lime, which reduces the water available to the retorted material for its own cementing reaction and reaction with the usable lime. Addition of 1 percent cement significantly increased q_u, i.e., 183.6 psi and 154.3 psi at 28- and 60-day cures, respectively. Further increases were obtained by adding 3 percent cement, i.e., 203.0 psi and 234.8 psi for 28- and 60-day cures, respectively. Although the q_u testing program on 1-1/2-in. maximum size particles was limited compared with the 3/4-in. maximum size previously described, the q_u values were higher for the larger particle sizes.

35. The basic parameters obtained from the K_o testing were E_d, ν, and K_o. The E_d values are indicators of strength and compression property variations. Values of E_d, ν, and K_o from the testing program are summarized in Table 4 and shown graphically as a function of one another and of q_u in Figures 11, 12, and 13. Modulus values, as expected, increased with increasing compaction effort; however, no distinct differences were noted between the 28- and 60-day cure specimens. Adding lime increased the modulus values, but consistent with the q_u test results, the higher percentage of lime resulted in a lower strength as compared with the lower lime percentage. Adding cement significantly increased the modulus values, following the same trends set by the q_u tests. Higher modulus values were obtained for specimens molded from 1-1/2-in. maximum size particles. Average K_o

values varied from 0.35 to 0.45 over the range of modulus values obtained. Average ν values ranged between 0.25 and 0.31 over the range of modulus values obtained.

36. A total of four specimens, two K_o and two q_u, were saturated prior to testing. In both q_u tests the strengths were higher for the saturated specimens compared with those of specimens molded at the same conditions and not saturated. Higher modulus and lower K_o values were obtained for the saturated specimens versus their unsaturated counterparts.

PART III: CONCLUSIONS

37. Whether disposal of retorted oil shales involves filling the surface canyons in the oil shale mine area, backfilling oil shale mines, or a productive use such as aggregates, the geotechnical properties of the shales will determine the performance of the disposal structure (i.e., embankment) or product (i.e., aggregates). During previous discussions, the important physical and engineering properties of raw and retorted oil shales from available sources have been defined and briefly discussed via available published information. Although the properties exhibited considerable variability, the data did provide insight into the behaviorial characteristics from a geotechnical point of view. Pertinent conclusions regarding the geotechnical properties are discussed in the following paragraphs with emphasis on the properties of retorted oil shale.

38. Published physical property data show that the apparent specific gravity of retorted oil shales generally range between 2.5 and 2.6. Retorted oil shales are generally well-graded materials regardless of the particle size (i.e., gravel, sand, silt, and clay) predominant in the gradation. Retorted oil shales are classified as GM, SM, or ML materials by the USCS depending on the amount of gravel present and plasticity of the fines. In the AASHTO System, retorted shales are classified as A-1 or A-3 materials. Retorted oil shales are generally nonplastic; however, measured plasticity indexes are less than 10 percent.

39. Compaction characteristics of crushed raw shale indicated optimum moisture contents between 1 and 8 percent and maximum dry densities between 77 and 90, pcf depending on the gradation and compaction energy. For retorted shales over the same compaction energy range, the optimum moisture content ranged between 18 and 31 percent and maximum dry density ranged between 77 and 103 pcf. The crushed raw shale and most of the retorted shales tested exhibited a generally flat S-shaped compaction curve in which the density decreased in the lower end of the moisture content range and then increased to the maximum value and began decreasing again.

40. Field compaction can be effectively achieved using routine compaction procedures and equipment. Vibrating compactors, either pad or drum, obtain maximum percent compaction with fewer passes than do conventional compaction equipment. Water added at the compaction site increases the efficiency of most compaction equipment. Adding water also reduces particle breakdown compared with compaction of dry material.

41. Permeability of retorted oil shales is variable and, like most material, is dependent on gradation, amount of compaction, and applied load. Field studies show that compaction significantly reduces the permeability when leaching of chemicals by rainwater is considered a potential environmental hazard.

42. As with permeability, the settlement or consolidation properties are variable. The material follows the accepted trends of lower densities resulting in larger settlements. Settlement properties were distinctly affected by the amount of carbonate decomposition of the retorted shales with low-carbonate decomposition shales settling 1-1/2 to 2 times as much as high-carbonate decomposition shales.

43. Retorted oil shales are not relatively hard materials since their resistance to degradation by external force, i.e., soundness, is generally less than minimum accepted values for concrete or base course aggregates.

44. Reported compressive strength of undisturbed raw shales ranged between 9,000 and 25,000 psi, with the lower strengths corresponding to low-kerogen content shales and increasing as the kerogen content increased. Sample orientation (i.e., parallel or perpendicular to bedding) had a slight effect on strength with the parallel to bedding samples yielding slightly higher strength. Reported modulus of elasticity values ranged between 0.83×10^6 and 6.025×10^6 psi and exhibited trends similar to those for compressive strength, kerogen content, and sample orientation.

45. Reported data on strength of compacted retorted shales showed that strength increases with (a) increasing molding water content, (b) increasing storage or curing time, and (c) decreasing seasoning or mellowing time. The combination of these factors and their variations

indicates that the strength of retorted shales is analogous to that developed in lime-stabilized soils: the strength is dependent on the development of pozzolanic reaction products or cementing agents between individual particles. Increasing strength with increasing water content indicates that the water is being used by the material to form the cementing agents; however, one data source[24] did show that strength decreases after reaching a molding water content (Figure 8) of approximately 15 percent. The rapid increase in strength with time is typical of strength that is dependent on cementing agents. In nearly all reported cases, the major portion of the strength was developed by or prior to the 14-day curing time.

46. Additives such as lime and cement showed distinct effects on strength characteristics. One percent hydrated lime increased the strength compared with that of the untreated material, but addition of 3 percent lime resulted in a decrease compared with the 1 percent strengths. This would indicate an excess of lime, which would have a tendency to reduce the water available to the shale to develop its own cementing agent or to react with the usable lime. Addition of cement at the 1 and 3 percent level resulted in continued strength gain with increasing percent cement.

47. K_o testing of retorted oil shales indicated that E_d values varied between 5,000 and 24,000 psi, depending on the gradation and compaction energy. Average K_o values ranged between 0.35 and 0.45 over the range of modulus values obtained. Average V values ranged between 0.25 and 0.31 over the same range.

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Table 1

Summary of Material and Sample Description and Location Information

Reference No.	Reference Date	Material	Location	Sample Description/Designation	Remarks
1	1950	Green River Formation	Rifle Oil Shale Mine, Rifle, Colo.	Raw shale, Designated Group No. 29 in Reference	Tests run on cores from vertical and horizontal core holes for high- and low-kerogen materials
2	1951	Green River Formation, Mahogany Ledge	USBM Oil Shale Demonstration Plant, Rifle, Colo.	Raw shale, 16 samples designated in two groups - "Six Selected Colorado Oil Shales" (6) and "Mineable Bed Samples" (10)	Tests run on core samples (3/4-in.)
3	1952	Green River Formation, Mahogany Ledge	USBM Oil Shale Demonstration Plant, Rifle, Colo.	Raw shale, retort feed	Gradation of crushed raw shale only data presented
4	1952	Green River Formation	USBM Oil Shale Demonstration Plant, Rifle, Colo.	Raw shale, retort feed	Gradation of crushed raw shale only data presented
5	1953	Green River Formation	USBM Oil Shale Demonstration Plant, Rifle, Colo.	Raw shale, retort feed	Gradation of crushed raw shale only data presented
6	1954	Green River Formation, Mahogany Ledge	USBM Oil Shale Demonstration Plant, Rifle, Colo.	Raw shale, retort feed	Gradations of raw shale for different crushers and mine run
7	1954	Green River Formation, Mahogany Ledge	USBM Oil Shale Demonstration Plant, Rifle, Colo.	Raw shale	Tests run on core parallel and perpendicular to bedding on roof and pillars by 3 different laboratories
8	1955	Green River Formation, Mahogany Ledge	USBM Oil Shale Mine, Rifle, Colo. (near Book Cliffs)	Raw shale, Designated Group No. 41 in Reference	Tests run on cores from vertical and horizontal core holes for high- and low-kerogen materials
9	1956	Green River Formation, Mahogany Ledge	USBM Oil Shale Demonstration Plant, Rifle, Colo.	Raw shale, retort feed	Gradation of mine run shale only data presented
10	1959	Green River Formation, Mahagony Ledge	USBM Anvil Points Mine, Rifle, Colo.	Raw and retorted shale	Gradation of shale feed and retorted shale only data presented
11	1960	Green River Formation, Mahogany Ledge	USBM Oil Shale Mine, Rifle, Colo.	Raw shale	Tests run on cores from vertical and horizontal core holes. Most information on crushers and corresponding gradations
12	1963	Green River Formation, Mahogany Ledge	USBM Oil Shale Mine, Rifle, Colo.	Raw shale	Tests run on shales following removal of organic constituents. Data include particle size distribution, specific surface area and, pore sizes
13	1964	Data same as presented in Reference 7 with some additional discussion			
14	1967	Green River Formation, Mahogany Ledge	Not specified in Reference	Retorted shale	Tests run on reheated retorted shales using 1-in.-diam. × 2-in.-high remolded specimens. Data not included in summary table because too many variables and too few samples were used.
15	1969	Green River Formation, Mahogany Ledge	Not specified in Reference	Retorted shale	Tests run on reheated retorted shales using 1-in.-diam. × 2-in.-high remolded specimens

(Continued)

Table 1 (Concluded)

No.	Date	Material	Location	Sample Description/Designation	Remarks
16	1970	Green River Formation, Mahogany Ledge	Below Mahogany Marker Colony Mine Above Mahogany Marker USBM Mine	Retorted shale Designated BM Raw and retorted shale Designated AM	Majority of data is taken from References 14 and 15. Remaining data include numerous variables. Data not included in summary tables
17	1971	Green River Formation, Mahogany Ledge	USBM Experimental Mine, Rifle, Colo.	Raw shale	Tests run on 3/4-in.-diam. × 1-1/2-in.-high cores of high pressures and temperatures to simulate insitu retorting. Data not included in summary tables
18	1974	Green River Formation	Parachute Creek Oil Shale Plant, Colony Development Operation	Retorted shale	Test data on parts 2, 4, and 5
19	1974	Green River Formation	USBM Anvil Points Mine, Rifle, Colo.	Raw shale	Tests run on low-, moderate-, and high-Kerogen shales
20	1974	Green River Formation	Various locations	Raw shale	Tests run at high temperatures and pressures to simulate insitu retorting. Data not included in summary tables
21	1975	Green River Formation	USBM Laramie Energy Research Center, Laramie, Wyo.	Retorted shale	Test run to evaluate use of retort shale as highway construction material
22	1975 (Feb)	Green River Formation	USBM Demonstration Plant Stockpile, Anvil Point, Colo.	Retorted shale (Phase II of Paraho Oil Shale Study). Designated: Size 1. < No. 4 Size 2. < 3/4 in. Size 3. < 1-1/2 in.	Tests run on remolded specimens blended to reproduce the original gradation of stockpiled material
23	1975 (Apr)	Green River Formation, Mahogany Member	USBM Experimental and Demonstration Facility, Paraho Oil Shale Project (Phase III), Anvil Points, Colo.	Retorted shale from pilot plant. Designated: Size 1. < 1-1/2 in. Size 2. < 3/4 in. Size 3. < No. 4 Samples taken from exit conveyor belt	Tests run on remolded specimens for high and low degrees of carbonate decomposition
24	1975 (Oct)	Green River Formation, Mahogany Member	USBM Experimental and Demonstration Facility, Paraho Oil Shale Project (Phase IV)	Retorted shale from semi-works plant. Designated: IV-1A, IV-1B, IV-1B2 Discharge Conveyor (Direct) IV-S1 Stockpile (Direct) IV-SC1 Stocking Conveyor (Direct) IV-1IH Discharge Conveyor (Indirect)	Tests run on remolded specimens representing direct and indirect heating modes of the retort plant
				Raw shale	Tests run on cores cut from block samples
25	1976 (Feb)	Green River Formation Mahogany Member	USBM Experimental and Demonstration Facility, Paraho Oil Shale Project (Phase V)	Compacted test fill using retorted shale from Semi-Works Plant	Percent compaction determined for various equipment and coverage combinations See sample IV-1B for lab properties
26	1976 (Jul)	Green River Formation Mahogany Member	USBM Experimental and Demonstration Facility, Paraho Oil Shale Project (Phase VII)	Raw shale Sample designations VII-1. Raw shale feed VII-2. Block samples (Feb 75) VII-3. Block samples (Dec 75)	Tests run on different gradations blended to meet desired conditions. Tests run on cores cut from block samples
27	1976 (Dec)	Green River Formation Mahogany Member	USBM Experimental and Demonstration Facility, Paraho Oil Shale Project (Phase VI)	Retorted shale. Infiltration ponds constructed of discharge conveyor material	Infiltration tests run to determine permeabilities

(Note: Separate report not prepared. Data appear in Chapter 10 of Reference 27.)

Table 2

Summary of Physical and Engineering Properties of Raw Oil Shale

Reference Number	Material/Sample Description or Designation	Apparent Specific Gravity	Moisture Content Percent	Density pcf	Apparent Porosity Percent	Modulus of Elasticity 10^6 psi	Poisson's Ratio ν	Modulus of Rupture 10^3 psi	Modulus of Rigidity 10^6 psi	Unconfined Compressive Strength, q_u 10^3 psi
1	Green River Formation									
	Vertical core hole									
	Low kerogen (2 observations)	2.31 (2.31-2.31)			3.2 (1.5-4.9)	3.77 (3.61-3.93)	0.16 (0.11-0.21)	1.9 (1.8-2.0)	1.645 (1.61-1.68)	21.75 (21.6-21.9)
	High kerogen (2 observations)	2.13 (2.02-2.24)			1.35 (0.51-2.2)	2.295 (1.89-2.7)	0.10 (0.02-0.18)	0.985 (0.87-1.1)	0.985 (0.84-1.13)	12.75 (12.5-13.0)
	Horizontal core hole									
	Low kerogen (2 observations)	2.355 (2.26-2.45)			8.6 (5.2-12.0)	6.025 (5.0-7.05)	0.265 (0.25-0.28)	4.45 (4.1-4.8)	2.375 (1.94-2.81)	25.7 (23.2-28.2)
	High kerogen (2 observations)	2.17 (2.08-2.25)			1.35 (0.24-2.1)	3.723 (2.87-4.47)	0.657 (0.45-0.94)	3.40 (2.0-4.6)	1.14 (1.0-2.42)	11.13 (9.6-13.4)
2	Six selected Colorado oil shales	2.02 (1.673-2.504)	1.18 (0.38-2.93)	(Bulk) 74.65 (60.4-98.8)						
7	Green River Formation, Mahogany Ledge									
	Lab 1, College Park, Md.									
	Roof cored parallel to bedding	2.18				3.1	0.58	3.0	0.98	--
	Roof cored perpendicular to bedding	2.25				1.8	-0.10	0.36	1.0	16.6
	Pillar cored perpendicular to bedding	--				--	--	--	--	22.7
	Lab 2, Columbia University									
	Roof and pillar cored perpendicular to bedding					1.869 (0.51-3.56)		4.38 (3.35-6.59)		12.78 (7.35-19.0)
	Lab 3, Pittsburgh, Pa.									
	Roof and pillar cored perpendicular to bedding					1.35		1.43		11.7
	Roof and pillar cored parallel to bedding									9.66
8	Green River Formation, Mahogany Ledge									
	Vertical core hole									
	High kerogen	2.025			1.0	0.83	0.18	4.0	0.465	10.0
	Low kerogen	2.25			1.1	3.575	0.145	1.13	1.535	15.3
	Horizontal core hole									
	Low kerogen	2.36				5.95	0.33		2.22	25.0
11	Green River Formation, Mahogany Ledge									
	Vertical core	2.25				3.66	0.12		1.59	15.1
	Horizontal core	2.36				5.95	0.30		2.22	25.0
19	Green River Formation									
	Low kerogen			139.6		3.80				24.9
	Moderate kerogen			140.0		1.47				10.9
	High kerogen			124.6		1.02				10.6

Summary o

Reference Number	Material/Sample Description or Designation	Specific Gravity		Gradation								Atterberg Limits		Compaction			
		Apparent	Mass	Maximum Particle Size, in.	>No. 4 (Gravel)	<No. 4, >No. 200 (Sand)	<No. 200 (Silt & Clay)	<0.005 mm (Clay)	D_{60}, mm	D_{10}, mm	C_u	Liquid Limit	Plasticity Index	Compaction Energy ft-lbs/ft^3	Optimum Moisture, %	Maximum Dry Density at Optimum, pcf	Maximum Dry Density at Half Optimum, pcf
24	Green River Formation, Paraho Oil Shale Project																
	Block 1 (Specimen 1-6)																
	Block 2 (Specimen 2-2)																
	Block 3 (Specimen 3-4)																
26	Green River Formation, Paraho Oil Shale Project																
	Sample VII-1																
	1-1/2 - 3 in. (shale feed)	2.11	1.99	3	100	0	0	0	--	--	---						
	3/8 - 3 in. (shale feed), Curve A			3	100	0	0	0	55	22	2.5						
	3/4 - 1-1/2 in. (shale feed)		2.20	1-1/2	100	0	0	0	--	--	--						
	-3/4 in. (shale feed +10% of -3/8 in.)			3/4	50	43	7	--	--	--	--						
	-3/8 in. (shale feed reject), Curve C	2.12		3/8	45	48	7	2	5.2	0.2	26						
	-1-1/2 in. (shale feed +10% of -3/8 in.), Curve D			1-1/2	84	14	2	0	23.0	1.5	15			6,200	6.0	88.3	
														12,375	8.3	90.3	
	3/8 - 1-1/2 in. (shale feed), Curve E	2.15		1-1/2	100	0	0	0	28	14	2			6,200	1.0	77.5	
														12,375	1.0	80.1	
	Sample VII-3																
	Raw shale cores from block sample (Avg. of 9 samples)																

Note: D_{60} = Grain-size diameter at 60 percent passing.
D_{10} = Grain-size diameter at 10 percent passing.
C_u = Coefficient of uniformity, D_{60}/D_{10}.
* δ_d = 79 pcf; Loading = 4 psi.
** δ_d = 80.7 pcf; Loading = 4 psi.

Table 3

Summary of Physical and Engineering Properties of Raw Paraho Study Oil Shale

Atterberg Limits		Compaction					Relative Density		Permeability, ft/yr				Settlement, % (Consolidation)				Tria	
									At Loading, psi				At Loading, psi				Frictio	
Liquid Limit	Plasticity Index	Compaction Energy ft-lbs/ft^3	Optimum Moisture, %	Maximum Dry Density at Optimum, pcf	Maximum Dry Density at Half Optimum, pcf	Maximum Dry Density at Air Dry, pcf	Density (100%) pcf	Loose (0%) pcf	50	100	200	1000	50	100	200	1000	ϕ	
									10,500*									
		6,200	6.0	88.3			84.8	72.6	14,500**								35	0
		12,375	8.3	90.3													39	0
		6,200	1.0	77.5			80.5	62.4					1.0	2.0	4.5	20.0		
		12,375	1.0	80.1									2.0	3.0	6.0	17.5		

araho Study Oil Shale

/yr		Settlement, % (Consolidation)				Triaxial Shear				Unconfined Compression			Los Angeles Abrasion	Comments
si		At Loading, psi				Friction		Cohesion psi						
200	1000	50	100	200	1000	ϕ	tan ϕ	C	C' (Saturated)	Moisture Content, %	Density, pcf	Unconfined Compressive Strength, psi		
														Modulus of Elasticity 10^6 psi / ν
												10,027 7,563 10,027		0.58 0.32 0.82 0.36 0.56 0.28 (25% of failure load)
													14	Angle at repose = 40°
										8.3	90.3	9.7		Average of 3 specimens
						35 39	0.70 0.81	22.9 19.4	15.3 13.9					
		1.0 2.0	2.0 3.0	4.5 6.0	20.0 17.5									
										1.3 (0.8- 2.5)	126.2 (109.1- 1385)	7540 (6320- 9720)		

Table 4

Summary of Physical and Engineering Properties of Retorted O

Reference Number	Material/Sample Description or Designation	Specific Gravity		Gradation								Atterberg Limits		Compaction					Relative Density		Permeability At Loadi	
		Apparent	Mass	Maximum Particle Size, in.	>No. 4 (Gravel)	<No. 4, >No. 200 (Sand)	<No. 200 (Silt & Clay)	<0.005 mm (Clay)	D_{60}, mm	D_{10}, mm	C_u	Liquid Limit	Plasticity Index	Compaction Energy ft-lbs/ft3	Optimum Moisture, %	Maximum Dry Density at Optimum, pcf	Maximum Dry Density at Half Optimum, pcf	Maximum Dry Density at Air Dry, pcf	Density (100%) pcf	Loose (0%) pcf	50	100
15	Green River Formation Reheated retorted shale																					
18 (Part 2)	Green River Formation Colony Development Operation Semi-works Plant (Avg of 14 observations unless otherwise noted)			3/8 (1/4-1/2)	8.2 (1.5-19.0)	59.9 (42.2-76.2)	31.1 (17.1-47.0)	--	0.71 (0.2-2.11)	0.032 (.014-0.05)	29 (4.7-111)			12,375	19.4 (15.7-21.8)	95.8 (88.2-100.4)						
														33,750	17.4 (16.6-18.1)	106.7 (106.5-106.8)						
														56,250	15.7 (14.2-17.2)	108.5 (107.8-109.2)						
18 (Part 4)	Green River Formation Colony Development Operation Semi-works Plant	2.525		3/16	0	47	53	--	0.095	0.0065	15	30	6	56,250	17.0	100.0			32.0 52.5 86.5 63			
18 (Part 5)	Green River Formation Colony Development Operation Semi-works Plant																					
21	Green River Formation Laramie Energy Research Center		1.85	3/4	53	47	0	0	7	0.074	95	--	NP									
22	Green River Formation, USBM Experimental and Demonstration Facility, Paraho Oil Shale Project			3	48	20	32	12	8.2	0.0045	1822	33	3									
	As received																					
	Size 1	2.53		3/16	0	37	63	--	0.060	0.0024	25	--	--	6,200	23.7	91.3	84.9	85.9				
														12,375	23.7	93.2	90.5	91.1			1.57	1.04
														56,250	19.9	99.5	96.1	95.0				
	Size 2	2.13		3/4	26	30	44	--	0.50	.0034	147	--	--	6,200	20.0	95.8	92.5	92.8				
														12,375	20.2	98.3	95.8	94.2			0.56	0.53
														56,250	15.3	104.6	102.5	99.2				
	Size 3	2.11		1-1/2	42	22	36	--	5.8	.0034	1705	--	--	6,200	18.5	99.2	94.4	93.8				
														12,375	15.5	103.2	95.8	95.8			1.32	1.07
														56,250	14.4	108.4	104.0	104.2				
23	Green River Formation, USBM Experimental and Demonstration Facility, Paraho Oil Shale Project																					
	High Carbonate Decomposition																					
	As received	2.56		3	76	17	7	2	13	0.21	62	--	NP									
	Low Carbonate Decomposition																					
	As received	2.58		3	73	20	7	3	12	0.033	364	--	NP									
	High Carbonate Decomposition																				(70 psi)*	(145 psi)*
	Size 1	2.56		1-1/2	79	14	7	--						0					82.3	59.2		
				1-1/2	54	28	18	--						6,200	22.0	77.0	76.5	73.6			2088	1016
				1-1/2	50	31	19	--						12,375	19.8	80.2	80.0	79.8			157	713
				1-1/2	48	32	20	--						56,250	22.0	88.8	87.0	88.1			51.0	40.1
				1-1/2	52	36	12							12,375	21.8	80.2	--	--			828	307
	Low Carbonate Decomposition																					
	Size 1	2.58		1-1/2	72	16	12	--						0					85.3	76.3		
				1-1/2	49	25	26	--						6,200	22.0	93.0	87.7	91.1			199.0	118.3
				1-1/2	45	19	36	--						12,375	22.0	96.6	94.6	96.1			167.6	140.4
				1-1/2	35	27	38	--						56,250	22.0	102.5	96.9	102.4			2.10	1.76
				1-1/2	52	24	24	--						12,375	24.0	96.6	--	--			2.30	1.52
	High-Carbonate Decomposition																					
	Size 2			3/4	70	20	10	--						12,375	19.8	78.6	--					

(Continued)

Note: D_{60} = Grain-size diameter at 60 percent passing.

D_{10} = Grain-size diameter at 10 percent passing.

C_u = Coefficient of uniformity, D_{60}/D_{10}.

* Loading conditions for Reference 23 only.

Table 4

...of Physical and Engineering Properties of Retorted Oil Shales

...ion			Relative Density		Permeability, ft/yr				Settlement, % (Consolidation)				Triaxial Shear				Unconfined Compression			Los Angeles Abrasion	Comments
					At Loading, psi				At Loading, psi				Friction		Cohesion psi						
...at Optimum, pcf	Maximum Dry Density at Half Optimum, pcf	Maximum Dry Density at Air Dry, pcf	Density (100%) pcf	Loose (0%) pcf	50	100	200	1000	50	100	200	1000	φ	tan φ	c	c' (Saturated)	Moisture Content, %	Density, pcf	Unconfined Compressive Strength, psi		
2- 0.4) 7 .5- 5.8) 5 .8- 9.2)													21.4 27.3 26.8	0.39 0.52 0.51	24 18 18	5 10 20		69.5 67.4 62.1	See Figures 4 & 5 for curving time effect		12 observations for std compaction, 2 observations for 60 percent modified and modified compaction
)			32.0 52.5 86.5 63						-- -- -- -- Final specimen tested at $W_{molding}$ - no inundation	15.5 10.5 0 0.5	18.0 13.0 .5 1.0	23.0 19.0 1.0 2.0									Consolidation specimens δ_{dry} = 56.5 pcf = 65.0 pcf = 86.6 pcf = 71.0 pcf
													35° 35° 35° 20°		6.3 12.5 19.4 0	 Q-test R-test (Back-pressure saturated)				48.5	w = 5-20%, δ_d = 85 pcf w = 5-20%, δ_d = 90 pcf w = 10%, δ_d = 95 pcf δ_d = 85-90 pcf
	84.9 90.5 96.1	85.9 91.1 95.0			1.57	1.04	0.72	--	1.3	1.8	2.2	12.8	32.4	0.635 (Q-test)	17.4	12.5	--	--	26.7		
6	92.5 95.8 102.5	92.8 94.2 99.2			0.56	0.53	0.61	--	2.8	3.4	4.8	--									
2 4	94.4 95.8 104.0	93.8 95.8 104.2			1.32	1.07	0.87	--	1.8	2.2	3.7	--	34.2	0.68 (Q-test	2.2	--				21.5	LAA Run on 1/2 - 1-1/2-in. material
	76.5 80.0 87.0 --	73.6 79.8 88.1 --	82.3	59.2	(70 psi)* 2088 157 51.0 828	(145 psi)* 1016 713 40.1 307	(300 psi)* 480 40.6 16.1 146	14.5	(70 psi)* 1.6 1.1 0.4 0.5	(145 psi)* 2.4 1.3 1.2 0.8	(300 psi)* 2.8 1.4 1.3 1.1	5.3	35.8 35.0 37.6 30.1	0.72 0.70 0.77 0.58 (S-tests)	13.2 12.5 13.9 48.6	9.0 3.5 18.7 38.2	-- --	-- --	22.6 64.8		Shear and permeability placement w = 0% 14-day cure
5	87.7 94.6 96.9 --	91.1 96.1 102.4 --	85.3	76.3	199.0 167.6 2.10 2.30	118.3 140.4 1.76 1.52	75.8 80.6 1.07 1.36	4.72	2.8 3.0 3.4 0.4	3.4 4.1 3.6 1.2	4.4 5.5 3.9 1.5	10.7	37.2 34.2 42.9 29.7	0.76 0.68 0.93 0.57 (S-tests)	13.2 9.7 13.2 22.9	5.6 9.7 13.2 13.9	--	--	10.4		Shear and permeability placement w = 0% 14-day cure
	--																--	--	22.6		

(Continued)

2

Table 4 (Continued)

Reference Number	Material/Sample Description or Designation	Specific Gravity: Apparent	Specific Gravity: Mass	Gradation: Maximum Particle Size, in.	Gradation: >No. 4 (Gravel)	Gradation: <No. 4, >No. 200 (Sand)	Gradation: <No. 200 (Silt & Clay)	Gradation: <0.005 mm (Clay)	Gradation: D_{60}, mm	Gradation: D_{10}, mm	Gradation: C_u	Atterberg Limits: Liquid Limit	Atterberg Limits: Plasticity Index	Compaction: Compaction Energy ft-lbs/ft^3	Compaction: Optimum Moisture, %	Compaction: Maximum Dry Density at Optimum, pcf	Compaction: Maximum Dry Density at Half Optimum, pcf	Compaction: Maximum Dry Density at Air Dry, pcf	Relative Density: Density (100%) pcf	Relative Density: Loose (0%) pcf	Permeability, ft/yr At Loading, psi: 50	Permeability, ft/yr At Loading, psi: 100	Permeability, ft/yr At Loading, psi: 200	Permeability, ft/yr At Loading, psi: 1000
23	(Continued)																				(70 psi)	(145 psi)	(300 psi)	
	Low Carbonate Decomposition																							
	Size 2			3/4	64	22	14	--						12,375	24.2	95.2	--	--						
	High Carbonate Decomposition																							
	Size 3			3/16	0	67	33	--						12,375	31.0	80.0	--	--						
	Low Carbonate Decomposition																							
	Size 3			3/16	0	48	52	--						12,375	24.0	90.5	--	--						
	High Carbonate Decomposition																							
	Size 1 crushed			3/16	0	76	24	4																
	80 percent size 1 + 20 percent size 1 crushed			1-1/2	55	33	12	--						12,375	19.5	85.0	--	--			6.5	2.6	1.8	--
	Raw shale			3/8	43	50	7	3																
	80 percent size 1 + 20 percent raw shale			1-1/2	73	20	7	--						12,375	17.5	82.7	--	--			130.0	56.0	49.2	--
	Low Carbonate Decomposition																							
	Size 1 crushed			3/16	0	34	46	5																
	80 percent size 1 + 20 percent size 1 crushed			1-1/2	56	27	17	--						12,375	24.2	96.7	--	--			1.5	1.19	0.30	--
	Raw shale			3/8	42	51	7	2																
	80 percent size 1 + 20 percent raw shale			1-1/2	68	22	10	--						12,375	19.0	97.4	--	--			147.3	29.0	17.4	--
24	Green River Formation Paraho Semi-works Plant-Direct Heating Mode																							
	Sample IV-1A			2	66	21	13	2				--	NP											
				3/4	33	34	33	--						12,375	20.7	91.2								
	Sample IV-1B	2.59		2	55	23	22	2				--	NP											
				3/4	23	41	36	--						12,375	25.5	89.0								
				1-1/2	43	26	31	2																
				1-1/2	43	28	29	--						6,200	23.7	88.0	85.8	85.8			15.0	5.5	1.7	--
				1-1/2	42	29	29	--						12,375	22.0	92.5	89.5	89.9			7.0	1.4	0.8	--
				1-1/2	33	31	36	--						56,250	22.0	98.7	96.4	96.4			1.1	0.6	0.08	--
	Sample IV-1B																							
	Initial			1-1/2	45	31	24	3																
	After permeability			--	32	36	32	5						12,375	22.0	95.5					0.8	0.4	0.3	--
	Initial			1-1/2	54	22	24	2																
	After compaction			--	43	28	29	--						12,375	22.0	92.5					7.0	1.4	0.8	--
	Initial			1-1/2	65	19	16	2																
	After permeability			--	48	27	25	4						12,375	22.0	95.5					1.6	0.6	0.4	--
	Initial			3/4	45	30	25	3																
	After compaction			--	36	36	28	4						12,375	22.0	91.0								
	Initial			3/4	55	25	20	3																
	After compaction			--	42	35	23	4						12,375	22.0	88.6								
	Initial			3/4	65	19	16	3																
	After compaction			--	43	29	28	--						12,375	22.0	90.5								
	Initial			3/16	0	56	44	6																
				--	0	53	47	7						12,375	25.5	89.5								
	Sample IV-1B2	2.59	1.83	2	52	35	13	4																
				1-1/2	51	37	12	3						0										
					33	52	15	--						6,200	22.0	87.5	86.2	86.5						
					32	52	16	--						12,375	22.0	94.8	91.2	92.2						
					26	58	16	--						20,000	22.0	94.0	92.8	93.8						
					24	59	17	--						56,250	22.0	98.9	96.1	97.6			0.3	0.25	0.15	--
																					0.75	0.75	1.7	--
				3/4	38	46	16	3						0										
					28	56	16	--						6,200	27.2	85.5								
					22	63	15	--						12,375	25.2	90.2								
					21	64	15	--						20,000	22.0	93.2								
					18	68	14	--						56,250	22.0	96.4								

(Continued)

Table 4 (Continued)

Maximum Dry Density at Half Optimum, pcf	Maximum Dry Density at Air Dry, pcf	Relative Density: Density (100%) pcf	Relative Density: Loose (0%) pcf	Permeability, ft/yr At Loading, psi: 50	100	200	1000	Settlement, % (Consolidation) At Loading, psi: 50	100	200	1000	Triaxial Shear Friction: φ	tan φ	Cohesion psi: c	c' (Saturated)	Unconfined Compression: Moisture Content, %	Density, pcf	Unconfined Compressive Strength, psi	Los Angeles Abrasion	Comments
				(70 psi)	(145 psi)	(300 psi)		(70 psi)	(145 psi)	(300 psi)										
--	--															--	--	10.4		
--	--										12.5	30.1	0.58 (S-test)	131.9	52.1					
--	--							1.8	2.5	3.7	12.1	32.2	0.63 (S-test)	45.1	20.8					
--	--			6.5	2.6	1.8	--	0.7	0.7	0.8	--									
--	--			130.0	56.0	49.2	--	0.8	1.0	1.2	--									As received reject
--	--			1.5	1.19	0.30	--	1.5	1.8	2.2	--									
--	--			147.3	29.0	17.4	--	2.4	4.8	5.6	--									As received reject
																22.0	--	17		
																22.0	--	24		
85.8 89.5 96.4	85.8 89.9 96.4			15.0 7.0 1.1	5.5 1.4 0.6	1.7 0.8 0.08	-- -- --	2.8 1.4 0.9	3.0 1.6 1.0	3.2 1.7 1.1	-- -- --	34.6 34.2 34.6	0.69 0.68 0.69 (S-tests)	19.4 27.8 36.1	15.3 24.3 29.2	22.0	89.0		68.0	Shear and permeability placement w = 0% 28-day cure on q_u
				0.8	0.4	0.3	--	0.8	0.8	0.8	--									
				7.0	1.4	0.8	--	1.4	1.6	1.7	--									
				1.6	0.6	0.4	--	0.7	0.8	0.9	--									
																22.0	91.0	161.8		28-day cure
																22.0	88.6	168.1		28-day cure
																22.0	90.5	163.5		28-day cure
																22.0	--	297.2		28-day cure
86.2 91.2 92.8 96.1	86.5 92.2 93.8 97.6			0.3 0.75	0.25 0.75	0.15 1.7	-- --	0.8 0.15	0.9 0.25	1.0 0.5	-- --									0-day cure 28-day cure
																22.0 24.0 24.0	-- -- --	142.4 206.9 218.8		7-day cure 28-day cure 60-day cure

(Continued)

2

Table 4 (Concluded)

Reference Number	Material/Sample Description or Designation	Specific Gravity: Apparent	Specific Gravity: Mass	Gradation: Maximum Particle Size, in.	Gradation: >No. 4 (Gravel)	Gradation: <No. 4, >No. 200 (Sand)	Gradation: <No. 200 (Silt & Clay)	Gradation: <0.005 mm (Clay)	Gradation: D_{60}, mm	Gradation: D_{10}, mm	Gradation: C_u	Atterberg Limits: Liquid Limit	Atterberg Limits: Plasticity Index	Compaction: Compaction Energy ft-lbs/ft3	Compaction: Optimum Moisture, %	Compaction: Maximum Dry Density at Optimum, pcf	Compaction: Maximum Dry Density at Half Optimum, pcf	Compaction: Maximum Dry Density at Air Dry, pcf	Relative Density: Density (100%) pcf	Relative Density: Loose (0%) pcf	Permeability, ft/yr At Loading, psi: 50	Permeability, ft/yr At Loading, psi: 100	Permeability, ft/yr At Loading, psi: 200
24	(Continued)																						
	Paraho Semi-works Plant-Indirect Mode																						
	Sample IV-I-1H	2.55	1.80	2	70	18	12	3				--	NP										
				1-1/2	68	21	11	2						0									
				--	47	40	13	2						6,200	22.0	93.9	90.5	89.0			71	52	30
					42	44	14	2						12,375	18.0	98.8	94.9	94.4			3.8	3.7	2.[illegible]
					38	43	19	--						56,250	18.0	105.8	101.6	102.1			2.0	2.5	2.[illegible]
				3/4	55	29	16	3						0									
					49	36	15	3						12,375	22.0	99.2							
	Paraho Semi-works Plant-Direct Heating Mode																						
	IV-S1			3/4										12,375									
				3/4										12,375									
				3/4										56,250									
				3/4										56,250									
				3/4										56,250									
	IV-SC1			3/4										56,250									
				3/4										56,250									
				3/4										56,250									
	IV-1B2																						
	+3 percent cement			3/4										56,250									
	+3 percent lime			3/4										56,250									
	IV-1B2 (K_o tests)			3/4	32	53	15	4	2.74	0.043	64			0									
				3/4										6,200	27.2	85.5							
				3/4										12,375	25.2	90.2							
				3/4										56,250	22.0	96.4							
				3/4		(plus 1 percent lime)								12,375	26.2	90.2							
				3/4		(plus 3 percent lime)								12,375	28.2	90.2							
				3/4		(plus 1 percent cement)								12,375	26.2	90.2							
				3/4		(plus 3 percent cement)								12,375	28.2	90.2							
				1-1/2	46	42	12	3	6.66	0.055	121			0									
				1-1/2										6,200	22.0	87.5							
				1-1/2										12,375	22.0	94.8							
				1-1/2										56,250	22.0	98.9							

Table 4 (Concluded)

mpaction			Relative Density		Permeability, ft/yr				Settlement, % (Consolidation)				Triaxial Shear				Unconfined Compression			Los Angeles Abrasion	Comments
					At Loading, psi				At Loading, psi				Friction		Cohesion psi						
Maximum Dry Density at Optimum, pcf	Maximum Dry Density at Half Optimum, pcf	Maximum Dry Density at Air Dry, pcf	Density (100%) pcf	Loose (0%) pcf	50	100	200	1000	50	100	200	1000	ϕ	tan ϕ	c	c' (Saturated)	Moisture Content, %	Density, pcf	Unconfined Compressive Strength, psi		
93.9	90.5	89.0			71	52	30	--	2.1	2.7	4.2	--									
98.8	94.9	94.4			3.8	3.7	2.9	--	1.2	2.0	3.8	--	29.2	0.56	3.0	2.9					
105.8	101.6	102.1			2.0	2.5	2.4	--	1.0	1.6	2.2	--		(S-test)							
99.2																	24.0	--	11.8		28-day cure
																	24.0	--	15.3		60-day cure
																	24.0	--	10.8		120-day cure
																					1-hour seasoning time
																	22.0	91.0	26.6	70%	28-day cure
																	24.0	92.5	26.8		28-day cure
																	24.0	95.0	27.8		28-day cure
																	24.0	95.0	28.5		60-day cure
																	24.0	95.0	65.3		120-day cure
																	24.0	95.0	42.0		28-day cure
																	24.0	95.0	45.9		60-day cure
																	24.0	95.0	66.7		120-day cure
																					1-hour seasoning time
																	23.0	96.4	314.9		28-day cure
																	23.0	96.4	280.6		28-day cure
													Deformation Modulus, psi	n	K_o	Number of Tests				Curing Time Days	Column headings pertaining to K_o test series
85.5													6,370	0.296	0.420	2		68.7	28		Specimens molded at W_{opt} and δ_{max}
													5,894	0.306	0.442	2		56.6	60		
													11,185	0.268	0.374	1		84.3	36		Saturated prior to testing
90.2													9,680	0.289	0.406	2		88.2	30		
													9,867	0.293	0.416	1		103.1	60		
													23,996	0.273	0.381			165.5	40		Saturated prior to testing
96.4													22,122	0.267	0.364	2		195.0	28		
													20,348	0.259	0.349	1		205.0	60		
90.2													12,037	0.300	0.429	2		159.2	28		
													10,092	0.292	0.415	2		136.2	60		
90.2													11,760	0.282	0.395	2		117.9	28		
													11,357	0.283	0.398	1		122.3	60		
90.2													13,166	0.289	0.406	2		183.6	28		
													10,379	0.293	0.417	1		154.3	60		
90.2													16,953	0.261	0.356	2		203.0	28		
													16,048	0.275	0.383	2		234.8	60		
87.5													4,765	0.311	0.453	1		61.7	28		
													8,478	0.293	0.417	1		91.9	60		
94.8													20,084	0.279	0.389	1		169.4	30		
													16,358	0.240	0.317	1		119.0	100		
98.9													51,427	0.203	0.256	1		209.5	37		

(Sheet 3 of 3)

2

Table 5

Summary of Field Compaction Test Results Paraho Semi-Works Plant Retorted Shale Research, Phase V

Direct Heat Retorting (from Reference 25)

Identification	Test Section Number	Layer Number	Roller Type	Number of Roller Passes	Laboratory Compaction: Moisture %	Laboratory Compaction: Dry Density pcf	Field Compaction: Moisture %	Field Compaction: Dry Density pcf	Field Compaction: Percent Compaction (D 698)	Gradation: % No. 200 Sieve: Before Compaction	% No. 200 Sieve: After Compaction	% No. 200 Sieve: Change	% No. 200 to No. 4 Sieves: Before Compaction	% No. 200 to No. 4 Sieves: After Compaction	% No. 200 to No. 4 Sieves: Change	% >No. 4 Sieve: Before Compaction	% >No. 4 Sieve: After Compaction	% >No. 4 Sieve: Change	Remarks
Laboratory Tests																			
Pilot Plant Phase III (Sample 2, Dark)			Drop Hammer (ASTM Standard)	D-698	0	96.1				12	36	+24	16	19	+3	72	45	-27	
				D-698	22.0	96.6													
				D-1557	22.0	102.5				12	38	+26	16	27	+11	72	35	-37	
Semi-Works Plant Phase IV (Sample 1-B)				D-698	0	89.9				24	29	+5	22	29	+7	54	42	-12	
				D-698	22.0	92.5													
				D-1557	22.0	98.7				24	36	+12	22	31	+9	54	33	-21	
Field Tests																			
Semi-Works Plant Phase V Moisture added at fill	A	1-4	Speeps-foot	6	20.0	93.5	17.3	91.2	98	11	24	+13	42	34	-8	47	42	-5	
	B			10	20.0	95.2	15.4	89.6	94	--	26	--	--	37	--	--	37	--	
	C			14	20.0	93.6	17.5	96.1	102	19	15	--	31	39	--	50	46	--	
	D	1-4	Rubber tire	6	20.0	96.7	15.6	95.7	99	20	12	--	35	29	--	45	59	--	
	E			10	20.0	94.7	16.0	91.5	97	15	24	--	30	36	--	55	40	--	
	F			14	20.0	90.9	19.3	92.8	102	24	21	--	17	40	--	59	39	--	
8-in. loose layer thickness	O-1	1-4	Vibrator pad	5	18.0	94.3	18.0	97.8	104	16	23	+7	41	44	+3	43	33	-10	
	P-1	1-4	Vibrator smooth	6	20.0	90.9	20.0	99.7	110	14	19	+5	41	42	+1	45	39	-6	
	M-1	1-4	Vibrator pad	4	18.7	91.9	18.7	99.5	108	15	17	+2	38	49	+11	47	34	-13	
			Vibrator smooth	4															
	N-1	1-4	Sheeps-foot	4	19.8	89.4	19.8	96.6	108	16	23	+7	40	45	+5	44	32	-12	
			Rubber tire	6															

(Continued)

Notes: Laboratory compaction and field percent compaction based on standard test compactive effort of 12.375 ft-lb/ft^3.
Field densities and "after compaction" gradations taken in layers 2 and 3 for 8-in. layer compaction and layer 6 for 12-in. layer compaction, unless otherwise noted.
Layer 2 'before compaction" gradations not representative and not included in averages. Others are layers 2 and 3 or layer 6, unless otherwise noted.

(Sheet 1 of 3)

Table 5 (Continued)

Identification	Test Section Number	Layer Number	Roller Type	Number of Roller Passes	Laboratory Compaction		Field Compaction			Gradation									Remarks
										% No. 200 Sieve			% No. 200 to No. 4 Sieves			% >No. 4 Sieve			
					Moisture %	Dry Density pcf	Moisture %	Dry Density pcf	Percent Compaction (D 698)	Before Compaction	After Compaction	Change	Before Compaction	After Compaction	Change	Before Compaction	After Compaction	Change	
Field Tests (Continued)																			
	R-1	1-4	Tractor	6	21.7	95.5	21.7	97.4	102	12	23	+11	34	44	+10	54	33	-21	
	POND 1	1-15	Vibrator smooth	7	--	--	22.1	100.6	--	--	25	--	--	42	--	--	33	--	
12-in. loose	A	5-7	Sheeps-	6	20.0	94.4	13.3	83.7	88	23	19	--	44	39	--	33	43	--	
layer	B		foot	10	20.0	95.0	11.8	86.5	91	24	24	0	42	40	-2	34	36	+2	
thickness	C			14	20.0	88.5	14.1	81.2	92	18	22	+4	33	48	+15	49	30	-19	
	D	5-7	Rubber	6	20.0	94.2	13.0	89.6	95	18	23	+5	36	41	+5	46	36	-10	
	E		tire	10	20.0	93.2	15.2	87.6	94	19	23	+4	34	45	+11	47	32	-15	
	F			14	20.0	90.9	15.8	87.9	97	20	22	+2	37	45	+8	43	33	-10	
	O-3	1-3	Vibrator pad	12	20.0	90.1	20.0	93.9	104	17	18	+1	42	48	+6	41	34	-7	
	P-3	1-3	Vibrator smooth	12	17.6	91.3	17.6	100.4	110	17	23	+6	45	43	-2	38	34	-4	
No moisture	G	1-4	Sheeps-	6	6.2	96.6	6.2	94.5	98	31	24	--	21	44	--	48	32	--	
added to	H		foot	10	3.7	97.2	3.7	94.6	97	30	25	--	13	41	--	57	34	--	
fill	I			14	6.8	95.1	6.8	91.7	96	36	27	--	15	40	--	49	33	--	
8-in. loose	J	1-4	Rubber	6	1.7	98.6	1.7	96.7	98	40	16	--	14	41	--	46	43	--	
layer			tire	10	1.9	98.9	1.9	98.1	99	38	19	--	19	40	--	43	41	--	
thickness				14	1.0	99.4	1.0	101.6	102	23	14	-9	21	36	+15	56	50	-6	
	O-2	1-2	Vibrator pad	6	6.5	93.9	6.5	92.2	98	17	18	+1	42	41	-1	31	31	0	Only 2 of 4 layers completed.
	P-2	1-4	Vibrator smooth	6	0	97.5	0	101.4	104	18	18	0	33	36	+3	49	46	-3	Layers 1 and 2 tested
	R-2	1-4	Tractor	6	4.6	92.7	4.6	94.2	102	10	22	+12	23	43	+20	67	35	-32	Very coarse material
	S-1	1-2	Tractor	10	5.2	92.4	5.2	92.3	100	13	24	+11	35	46	-11	52	30	-22	
	POND	1-16	Haul-spread	--	3.7	93.5	3.7	91.5	98	15	21	+6	30	40	+10	55	39	-16	4 truck passes and 2 loader passes on bottom lining. 2 loader passes on side lining plus travel
	G	5-7	Sheeps-	6	0.7	92.2	0.7	89.1	97	19	17	-2	44	42	-2	37	41	+4	
	H		foot	10	0.4	91.6	0.4	89.8	98	13	16	+3	35	42	+7	52	42	-10	
	I			14	0.5	92.0	0.5	88.1	96	18	16	-2	32	41	+9	50	43	-7	

(Continued)

Table 5 (Concluded)

Identification	Test Section Number	Layer Number	Roller Type	Number of Roller Passes	Laboratory Compaction		Field Compaction			Gradation									Remarks
										% No. 200 Sieve			% No. 200 to No. 4 Sieves			% >No. 4 Sieve			
					Moisture %	Dry Density pcf	Moisture %	Dry Density pcf	Percent Compaction (D 698)	Before Compaction	After Compaction	Change	Before Compaction	After Compaction	Change	Before Compaction	After Compaction	Change	
Field Tests (Continued)																			
	J	5-7	Rubber tire	6	0.5	91.5	0.5	84.1	92	13	16	+3	31	46	+15	56	38	-18	
	K			10	0.7	94.5	0.7	92.4	98	14	18	+4	31	42	+11	55	40	-15	
	L			14	1.9	96.7	1.9	94.4	98	12	20	+8	30	41	+11	58	39	-19	
	0-4	1-2	Vibrator pad	6	2.1	96.2	2.1	91.7	95	17	16	-1	38	36	-2	45	48	+3	Only 2 of 4 layers completed. Layers 1 and 2 tested for gradation. Only 1 density test made in layer 2
	P-4	1-3	Vibrator smooth	9	3.5	92.3	3.5	90.7	98	15	20	+5	27	36	+9	58	44	-14	
	S-2	1-3	Tractor	10	3.8	96.7	3.8	93.3	97	12	22	+10	33	41	+8	55	37	-18	
					--	93.9	--	93.0	99	16	20	+4	36	42	+6	48	38	-10	Average of all tests
Summary of all field tests					19.8	92.8	17.1	93.0	100	16	21	+5	38	42	+4	46	37	-9	Average for all tests in wetted area
					2.8	95.0	2.8	93.1	98	15	19	+4	34	41	+7	51	40	-11	Average for all tests in nonwetted area

APPENDIX A: OIL SHALE RETORTING PROCESSES

1. Three retorting processes are used to extract oil from oil shale:

   a. Solid to solid heat transfer (Tosco process).

   b. U. S. Bureau of Mines gas combustion method.

   c. Gas to solid heat transfer (Petrosix process).

Tosco Process

2. Figure A1 shows a flow diagram of the Tosco process. In this process the shale is mixed with preheated balls in a horizontal rotating kiln. The gas produced is of high quality and can be refined for its valuable components. The process can take a large amount of finely crushed shale particles. The process efficiency is further increased by the reduction of particle size by the crushing action of the balls. One disadvantage of this process is that it produces a large amount of fine waste material which may increase disposal problems.

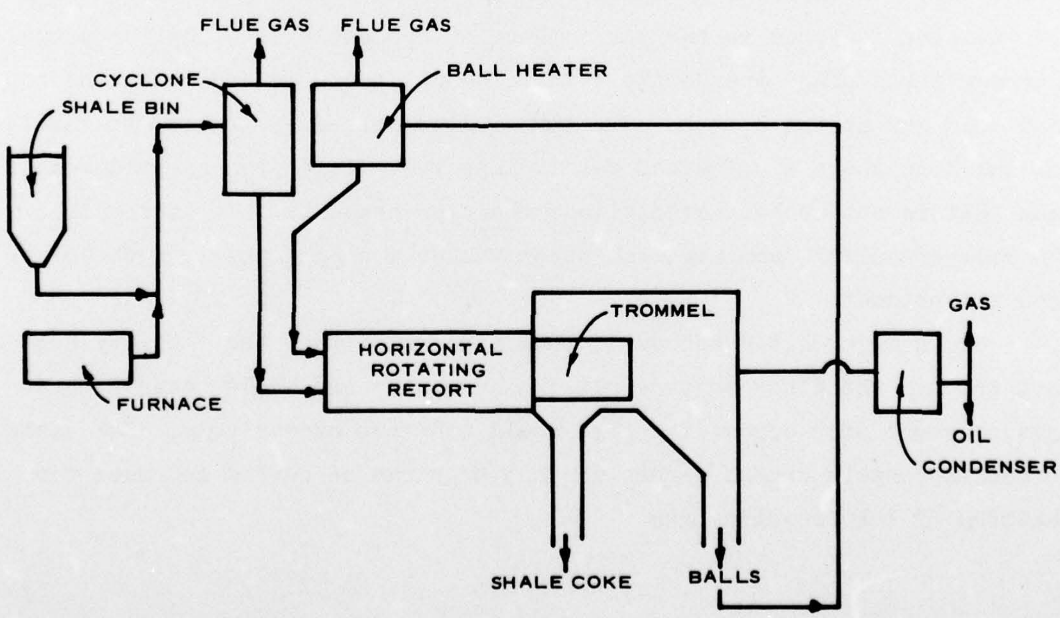

Figure A1. Tosco process

Gas Combustion Process (Paraho)

3. Figure A2 shows a flow diagram of the U. S. Bureau of Mines gas combustion process. A stream of crushed shale enters at the top and is preheated by the combustion gases. Air and recycling gas are injected at the midpoint and are burned, bringing the oil shale above this point to retorting temperature. Some of the spent shale is consumed as fuel in the burning process. The gas entering at the bottom is heated by the burnt shale before it is ignited.

4. Major disadvantages of this process are that it produces a low Btu gas product and it is not able to process the fines that result from crushing the shale. It has the advantage of producing a waste material in the form of a soft friable rock containing approximately 2 to 3 percent carbon.

Petrosix Process

5. Figure A3 shows a flow diagram of the gas to solid heat transfer system for extraction of oil from oil shale. This process has many of the same features as the gas combustion process except that no actual burning takes place inside the kiln. The oil shale is fed in at the top and cold gas at the bottom. The temperature increases toward the middle of the kiln where a preheated gas is injected. This process produces a gas that is not contaminated with combustion products. It is possible to recover sulfur, ammonia, and other valuable components from the high-Btu gas product.

6. A major disadvantage of this process is that the facility cannot process the fines that result from crushing the shale because the gas pressure drop across the kiln would increase excessively. The waste products contain enough carbon so that they can be burned and used for heating of the recycling gas.

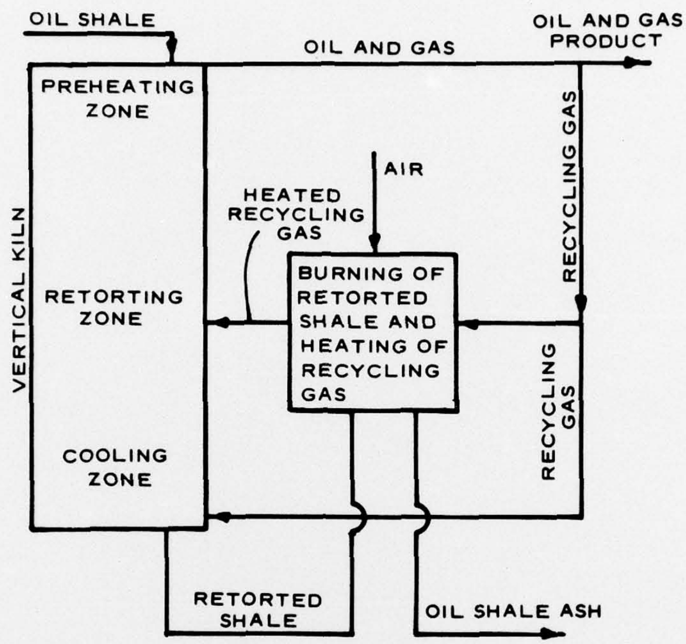

Figure A2. Gas combustion process

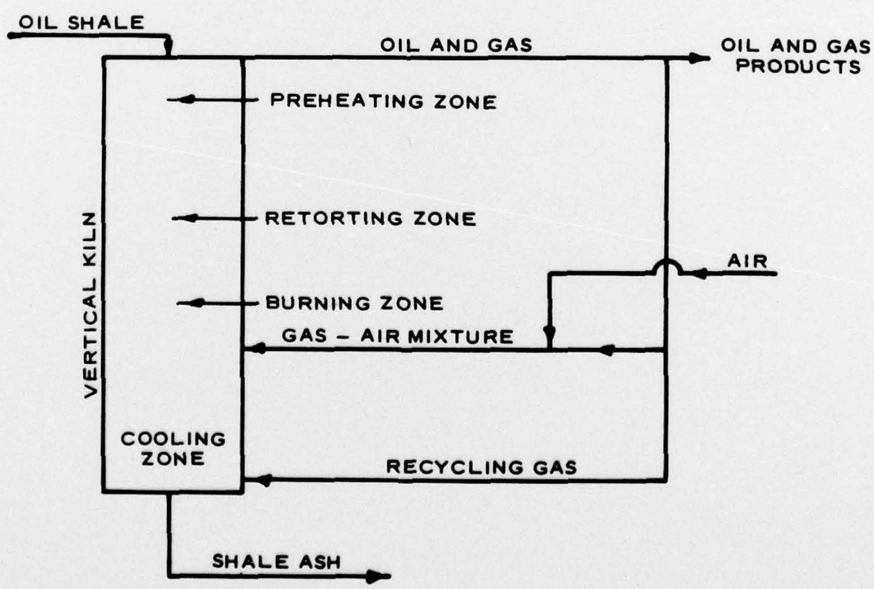

Figure A3. Petrosix process

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Snethen, Donald Ray
A review of the physical and engineering properties of raw and retorted oil shales from the Green River Formation / by Donald R. Snethen, Warren J. Farrell, Frank C. Townsend. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
40, [13] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-78-3)
Prepared for Bureau of Mines, U. S. Department of the Interior, Spokane Mining Research Center, Spokane, Wash., under Interagency Agreement H0262064.
References: p. 38-40.

1. Disposal. 2. Green River Formation. 3. Oil shales. 4. Mine wastes. 5. Rock properties. I. Farrell, Warren J., joint author. II. Townsend, Frank Charles, joint author. III. United States. Bureau of Mines. Spokane Mining Research Center. IV. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; S-78-3.
TA7.W34m no.S-78-3